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SAND-BED FILTRATION OF AEROSOLS: A REVIEW OF PUBLISHED INFORMATION ON THEIR USE IN INDUSTRIAL AND ATOMIC ENERGY FACILITIES

by

R. A. Juvinall, R. W. Kessie,
and M. J. Steindler

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Chemical Engineering Division

June 1970

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ABSTRACT

This report reviews the principles of operation, design, cost, and performance of sand-bed filters for removing aerosols from gas streams. The sand-bed filters described remove dust from industrial gas and air streams, serve as emergency filtration systems for large nuclear-energy facilities, or remove radioactive aerosols from the off-gas of nuclear-fuel-reprocessing plants or from gas-coolant streams of nuclear reactors. Experience with full-scale sand filters is reported, as well as the results of laboratory-scale investigations.

Utilization of sand filters in ventilation systems of protective shelters (for humans) is reviewed in relation to the ability of sand filters to resist the destructive effects of air pressure, shock, high temperature, thermal shock, chemical attack, and moisture. The life and initial cost for sand-bed filters are compared with those for fibrous filters.

The effects on filter operation of physical parameters such as the size and shape of sand particles, the composition and thickness of sand layers in a filter, filter design, and the design of bed containment structures are discussed. Filtration mechanisms are described, as are several alternative procedures for regenerating sand filters.

The relationship of filter life, collection efficiency, and air-handling capacity to the filter design and operating conditions appropriate for a specific filter application is described. Important variables are aerosol size, composition, and concentration and gas throughput rate.

1. INTRODUCTION

Filters consisting of graded layers of sand have been used to remove radioactive particles from ventilation off-gas streams of facilities processing irradiated nuclear fuels. Because of their resistance to heat, shock, and chemical attack, such filters are important to the safe operation of facilities handling highly radioactive materials.

This review is designed to collect into a single document all readily available information on sand-bed filters and thus represents a state-of-the-art report. This review should be a convenient source of information for those who wish to design, build, test, and use sand-bed filters.

Some designs of deep, graded sand-bed filters have significant advantages for specific applications in the filtration of aerosols. These advantages are primarily related to the ruggedness that can be designed into a sand-bed filter for a variety of relatively severe conditions of operation such as high temperature, thermal shock, air-pressure shock, ground acceleration, and chemical attack. The disadvantages of sand-bed filters, in comparison with other types of aerosol filters such as high-efficiency fiber filters, are higher cost, higher pressure drop, and a lower aerosol-collection efficiency. For extremely critical applications, it may be advantageous to use a combined series of filters including both sand-bed and high-efficiency filters to eliminate some of the disadvantages of either type used alone.

1.1 DEFINITIONS AND SCOPE OF LITERATURE SEARCH

Filtration of aerosols by sand and other granular materials is generally thought to represent a very specialized subject, with limited applications in the total field of dust, fog, mist, fume, and smoke removal; however, a rather thorough literature search has revealed considerable diversity, both in physical concepts and the variety of applications of fixed and moving beds. Fluidized beds are discussed in this report only incidentally, i.e., where performance of fluidized beds is compared with performance of fixed beds.

The literature searched includes *Chemical Abstracts*,

1907 through July 1969; *Abstracts of Declassified Documents*, July 1947 through June 1948; *Nuclear Science Abstracts*, July 1948 through July 1969; and *Scientific and Technical Aerospace Reports*, 1963 through July 1969. *Abstracts of Classified Reports* were searched through March 1967. Information contained in this review was obtained from original documents subsequently examined as a result of the abstracts searched.

Gibbs in his book *Clouds and Smokes* (1924) first used the term *aerosol* to include all the various dispersed systems in air–dust, fog, mist, fumes, and smoke. Definitions of the latter terms, based on those by White and Smith in their book *High Efficiency Air Filtration* (1964), are given below. A more thorough treatise is found in *Particulate Clouds: Dusts, Smokes, and Mists* by Green and Lane (2nd Ed., 1964).

1. *Dust*: Aerosols formed by such operations as crushing, blasting, grinding, or machining, which involve the disintegration of matter into airborne particles, generally coarser than those of fumes, smoke, mists, and fogs.

2. *Mists or fogs*: Liquid particles of various sizes formed by the condensation of vapors on suitable nuclei or by the atomization of liquids.

3. *Fumes*: Particulates usually less than 1 μm, formed by sublimation, combustion, or condensation.

4. *Smoke*: Particulates smaller than fumes and formed in similar processes, but having considerable optical density.

Additional terms frequently used in the ensuing discussion include:

1. *Particle size* is usually the average or equivalent diameter expressed in microns (symbol: μm; 1 μm = 10^{-6} m), but some authors use *particle radius* in lieu of *particle size.*

2. *Collection efficiency* is the percentage of particulate matter removed compared to that present in the air stream just upstream from the filter, and it can be expressed on the basis of either number of particles or total weight. However, it is necessary to distinguish between these two ways of calculating collection efficiency. Collection efficiency has a higher value when based on the weight of the particles removed, since larger particles are more easily removed and weigh more. An expression of efficiency must consider the spectrum of the particle sizes involved.

Table 1.1, compiled by Stanford Research Institute, summarizes the spectrum of particles and gas dispersoid characteristics, as well as methods of analysis and recommended gas-cleaning equipment. Note that packed beds such as sand or coke are recommended for aerosols with diameters in the range of 0.01 to 100 μm.

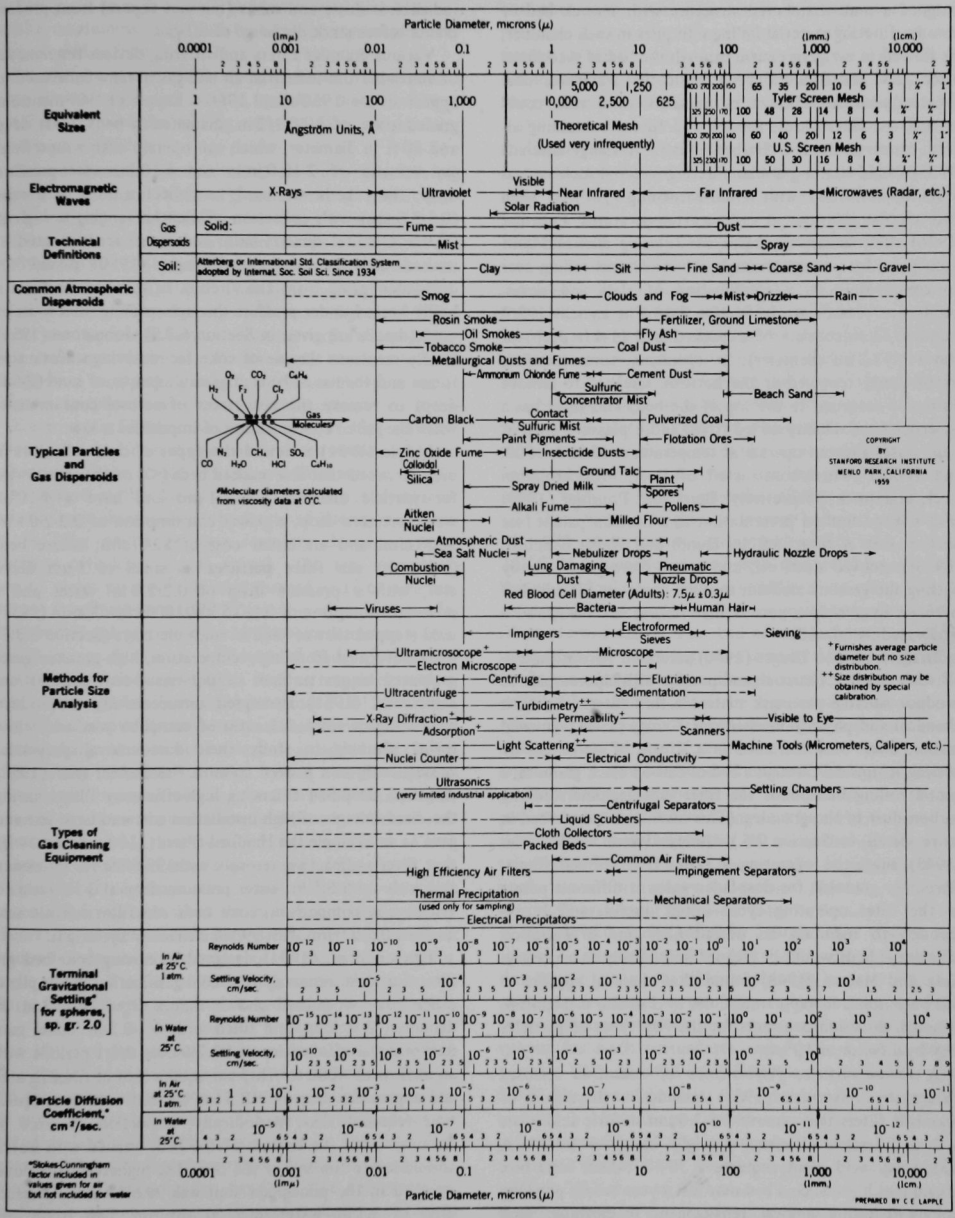
1.2 HISTORICAL REVIEW

1.2.1 Industrial Applications of Sand and Granular Filters for Aerosol Removal

A historical review of the literature indicates that with the increased industrialization of the nineteenth century, there arose an awareness of the need for dust respirators and dust-removal devices. One of the proposals of this era was that of Solvay (1889) who patented a filter to remove dusts and vapors from gases flowing upward through it. A cylindrical granular bed of sand or fibrous bed of asbestos was arranged in layers of increasing fineness upward from a foundation bed of coarse gravel or pebbles. A steam jacket was added to the vessel if a condensable vapor was to be removed; an internal rake or scraper on a central vertical shaft provided cleaning during operation. This pioneer patent contained many of the ideas later incorporated into the design of large coke beds for the removal of sulfuric acid mists and large sand beds for the removal of radioactive particulates.

The early decades of the twentieth century produced a series of diverse patents involving sand or granular filters. A filter for corrosive liquids, vapors, and gases designed in 1914 by Porter consisted of 75-85% sand and 25-15% powdered glass fused together at high temperatures. Fiechter (1919) proposed drawing a gaseous medium downward through a layer of sand on a movable-plan sieve (see Section 7.6 for details). Later (1922), he patented a horizontally moving sieve on an endless belt carrying a layer of sand, through which gas could be filtered under suction or pressure, as described in Section 7.6. Wells and Fogg (1920) describe lead-lined boxes of coke used to filter the acid spray or mist generated in the contact process of sulfuric acid production. Such boxes are 30-40 ft wide, 50-60 ft long, and 12-15 ft deep, with central drainage at the bottom. The coke (1/4-3/8 in.) is carefully sized and washed. The volume of gases filtered results in the collection of ~30 tons of sulfuric acid daily. Klärding (1921) suggested cleaning hot blast furnace and generator gases before discharge by passing them through a granular material contained between two screens (Section 6.3.3). Nordström (1924) used a tower of granular filtering material to separate dust and smoke from gases in processes involving cement burning, manufacture of chloride of lime, and copper smelting. In the same year, Thomson and Nisbet filtered dust-laden blast furnace gases through a downward-moving ballast screen falling over louver-like slats, and Donaldson removed dust from hot gases (from the burning of crushed pyrites in Herreshoff roasters) by passing the gases at ~600 cfm through a 2 ft^2 tower with a 3-ft-deep coke bed above rill at a 1-3/4-in. water-gauge loss of pressure. All such devices were provided with a suitable means of cleaning or regenerating the dirty granular material, which was removed at the bottom; cleaned material was conveyed to a hopper at the top. Gibbs (1922) in a review article, "The Industrial Treatment of Fumes and Dusty Gases," mentions dry filtration through coke and sand, as well as passing smoke through absorption towers of coke, gravel, slag wool, coarse sand, asbestos, etc., against a descending stream of water.

Table 1.1. Characteristics of Particles and Particle Dispersoids



Similar devices were described in patents granted in 1930-1950 and intermittently to the present. Lynch (1930) designed a multichambered structure with a thick bed of granular filtering material falling into piles in each chamber; gas flowed in a zigzag course through the bed at ≤10 linear ft/sec. Lévi and Blume (1934) found that water-insoluble silicates such as silicates of magnesia and talc could be used to filter gases, vapors, and fumes containing arsines; concurrently, I. G. Farbenindustrie Aktiengesellschaft (1935) found that a granular filtering material such as sand could be cemented with a self-hardening synthetic resin into a coherent mass at ordinary temperatures. Fournier (1936) designed an apparatus for filtering dust and soot from gases by passage through a bed of sand falling over horizontal slats or a combination of slats and sieves. (Additional details are in Section 7.6.) The Lynch (1936) granular filter consists of a packed bed (1-4 ft deep) of gravel (1/2-1 in. diameter); in operation, some gravel is continuously removed at the bottom, screened to remove dust, and returned to the top of the bed. This filter has a superficial gas velocity of ~3 ft/sec and a pressure drop of 1 in. water and can operate at temperatures of 850, 1500, and 2000°F when constructed of steel, high-chromium steel, and brick, respectively. Berry and Fournier (1939) gave a more limited presentation in a German patent (see Section 7.6). A filter unit by Hundt and Weber G.m.b.H. (1938) removed dust, oil, and water from gas or air by passing the gaseous medium through a porous filter bed of coke or hygroscopic porous material, a felt liner, and a perforated metal wall.

Dragerwerk and Drager (1940) saturated porous materials such as silica, charcoal, and pumice with chloroamide to produce suitable gas mask materials that filtered by both chemical and physical mechanisms. Carney (1944) removed carbon black dust entrained in a stream of air or gas by passing it upward through a bed of carbon black granules; a gentle rolling motion of the filter unit agglomerated the carbon dust to the granules. (This invention is described in more detail in Section 7.6.) Hurley, Fitton, and Davies (1945) suggested operating a series of fixed-bed filters, fibrous or granular, for dust-laden gases at different points in the filter operating cycle—initial, useful, and breakthrough—to maintain an overall high rate of filtration efficiency; beds would be cleaned individually as necessary. Katz and Macrae (1948) found that charcoal appears to filter aerosols and vapor molecules by a similar mechanism, although diffusion constants for the two types of particles vary by a factor of 10^5.

A review article, *Performance of Industrial Aerosol Filters*, by Silverman (1951) includes a discussion of coke-bed filters that remove 0.5-3.0 μm sulfuric acid mists with a filtration efficiency (weight basis) of 99.9%. A 30-ton/day acid plant requires a 30-40-ft-diam coke box several feet high. Such a bed may last a year before plugging and necessitating removal, replacement, or cleaning. Such large coke beds were the basis for a design by Lapple (1948a) for the large sand beds at Hanford to remove radioactive dusts and mists (but not vapors) from process plants before stack discharge of off-gas.

Various granular filters and filtering devices for removal of aerosols from industrial air and gas streams continued to appear in the 1950's and 1960's. Lapple (1950) mentions graded coke of 1/40-1/2 in. diameter in beds 2-6 ft deep and 30 ft in diameter, which can operate with a superficial gas velocity of 2-10 ft/min and 1-10 in. water-pressure drop; these beds are used to collect sulfuric acid mist (0.5-3.0 μm) with collection efficiencies ranging as high as 99.9%. Granite, quartz, sand, and gravel are also used in packed beds. Mercier and Ehlinger (1950) passed hot dust-laden gases from the firebox of a boiler or from a boiler heated under pressure through rotating filter units of sand (details are given in Section 6.3.3). Johnstone (1951) briefly mentions the use of coke for removing sulfuric acid fumes and the use of beds of granite, quartz, or sand (2-6 ft deep) to remove the last traces of aerosol contaminants when the initial concentration of impurities is low.

Lapple (1951) reviewed the types of dust collectors in use. He noted that fine packed beds (<4 mesh) are suitable for particle diameters of <1 μm and have a 1-10 in. water pressure drop, a power consumption of 0.2-2.0 kW/1000 cfm, and an initial cost of $2-5/cfm; coarse beds (>4 mesh) can filter particles as small as 5-μm diameter, with a pressure drop of 0.2-2.0 in. water and a power consumption of 0.1-0.5 kW/1000 cfm. Veron (1951) used stepped tiers of sand in multiple trays (Section 6.3.3) to remove dust from high-temperature, high-pressure gases generated in gas turbines or pulverized-coal combustion. First *et al.* (1951) attempted unsuccessfully to produce electret discs from 1:1 ratio of carnauba wax and white rosin, planning to study their dust-removal properties subsequently in a packed column. Friedlander *et al.* (1952) classified deep-bed filters as high-efficiency filters having the disadvantages of high installation cost and large size and gave as an example the Hanford filters (110 by 48 by 14 ft) that filter radioactive aerosols with 99.5-99.8% efficiency and with a 4.5-5.5-in. water pressure drop at 3-5-ft/min air velocity; in comparison, coke beds can filter sulfuric acid mists of 0.5-3.0 μm with 99.9% efficiency by weight.

Egleson *et al.* (1954) designed a moving coke-bed gas filter for dust removal in a coal-gasification pilot plant; preliminary work had shown that a fixed bed, 3 in. in diameter, 3 ft long, and filled with 0.1-0.3-in. coke, gave dust-removal efficiencies of 99.7% over short periods with an airflow of 4000 ft^3/(hr) per square foot of filtering area and a pressure drop of <2.5 in. water. Continuous operation required that, periodically, a portion of coke be removed from the bottom of the bed, washed with water, and added to the top of the bed. The highest dust removal attained in the pilot-plant unit was 99.8% with a pressure drop of 3.5 in. water in a 20.2-hr run. This study also

suggested that 4-8 mesh broken silicon carbide or bauxite be used as the filter material and that dust be screened out of hot gases in a dry filter bed; since spherical balls of mullite or alumina allow dust to escape, irregular granules are preferred as filter material.

Wainwright *et al.* (1956) reported 99.4% dust removal from synthesis gas and a 12-in. pressure drop (see Section 7.6). He used the moving coke-bed filter designed by Egleson *et al.* (1954).

The mechanisms involved in electrostatic filtration of aerosols in fixed and fluidized granular beds were studied at the Air Cleaning Laboratory at Harvard University from 1955 to 1958. Interim reports were issued by Dennis *et al.* (1959a, 1959b, 1961); summary reports are by Anderson and Silverman (1958, 1959). They observed that triboelectrification or friction charging of fibrous and granular filter media can improve collection efficiency with no increase in flow resistance; however, fibrous media do not hold a charge for a long period, and so granular media—principally polystyrene spheres—were used in these studies.

Electrostatic filtration forces arising from charges on the aerosol particles, from charges on the filter media, and from interaction of the aerosol charges and filter surface charges were studied at the Air Cleaning Laboratory. Polystyrene granules were charged in situ by means of interspersed wires in the filter matrix or were remotely charged using a vibrating cylindrical Lucite trough. The test aerosol of gentian violet microspheres was charged to 18-64 electron charges (positive)/particle by a spinning disc generator. A fixed bed of polystyrene granules (280-μm diameter) with a surface charge density of 0.09 esu/cm^2 had a 64% collection efficiency for atmospheric dust as compared with a 96% efficiency for a fluidized bed expanded to 120% of the original bed depth. Polystyrene granules possess an intrinsic bipolar charge at zero net levels, and an added net charge acquired by triboelectrification. Both charges increase filtration performance. Heating for 2 hr at 80°C causes the granules to reverse their charges; mixed beds of heated and unheated materials have decided bipolar effects. From resistance to airflow data, a parametric relationship was established to estimate the actual interstitial (or jet) velocity in fixed beds from the superficial-bed properties. Theoretical collection efficiency parameters for fixed and fluidized beds use the concept of target efficiency of a single sphere. With a 1.00-μm (Mg) aerosol having a net charge of +18e/particle and a grounded bronze media (D_c = 0.92 mm) in the fixed-bed state, impaction curves were obtained for a round jet or a single isolated sphere using the jet velocity determined from a derived correlation and thus substantiating the jet theory. Various equations are given for correlating data in the tests. A fluidized bed of heated and unheated polystyrene granules will filter five times as efficiently (based on target efficiency) as a bed of grounded conducting media, handling over two times as much air volume at equivalent flow resistance.

Weinands (1957) developed a free-flowing filter medium with enlarged surface area by coating gravel with adhesive and then with finer-grained materials such as sand and granular plastic. Scott and Guthrie (1959) conducted studies with fluidized beds of silica gel; removal efficiencies were correlated with superficial gas velocities in fluidized and packed beds. Dennis *et al.* (1960) designed an institutional incinerator for low-level radioactive wastes. It used an 8-in. layer of 1/4-in. gravel to screen out coarse particulates at 200-800°F and a 4-in. sand seal between the main burning chamber and the afterburner to reduce air leakage and offer easy access for repair. (Additional details on this incinerator are presented in Section 6.3.3.)

New industrial uses of granular filters continued steadily into the 1960's. Knapsack-Griesham Aktiengesellschaft of Koln, Germany (1960), devised a method of purifying metal vapors, especially superheated magnesium vapor, by passing them through loose-flowing granular inert material such as coke (see Section 6.3.4); the initial vapor contains ~96.5% Mg, compared with 99.93% in the purified vapor. Strauss and Thring (1960) suggested that coarse granular refractory materials be used to reduce fumes from open hearth furnaces; they observed that high-temperature insulating brick ~5/16-in. particles (7 B.S. mesh) with a 10-1/2-in. bed depth gave an average collection efficiency of ~89% at an average gas velocity of 1.33 ft/sec and 251°C. (Additional data are given in Section 3.3.3.) Further studies by Thring and Strauss (1963) on the effect of high temperature on particle-collection mechanisms in pebble filters showed that a 9-in. bed of crushed brick at 400°C can preheat an incoming gas stream by 160°C; if gas flow (as in an open hearth and regenerator) is reversed, the pebble filter could replace the regenerator, requiring less space and effecting >90% reduction of fumes in exit gases. McCormick *et al.* (1963), in a brief review of "granular-bed separators," mentions sand filters and the Lynch (1936) granular filter. The Société des Produits Azotes (1961a) patented a method for removing dust from electrometallurgical furnace gases by passing the gases through filters of refractory materials such as quartz, coke, or minerals of the kind that are treated in the furnace. However, materials used as filters are not discharged into the furnace.

Krasovitskii and Zhuzhikov (1963) made calculations showing that separation of dust from a dust-gas mixture flowing at constant velocity through a sand filter is analogous to processes involving a gradual clogging of the filter. Silverman (1964) devised an automatic monitoring system for stack particulates, using pneumatically transportable 100-μm solid or hollow glass spheres that give >90% filtration efficiencies in a 1-cm deep-bed; subsequent analysis to determine particulate concentration in the stack gases is possible by direct weighing, chemical stripping, tuned coil disruption, or X-ray absorption. White and Smith in *High Efficiency Air Filtration* (1964) state that although deep-bed filters of crushed flint, sand, or coke packed with

progressively finer grains are reported to have efficiencies of 99.9% by weight for 0.5-3.0-μm particles, the trend in recent years is toward high-efficiency fibrous filters, which is the major subject of their book.

Goldman (1964) states that gravel-bed filters have been successful in large-pore, wear-resistant, high-temperature filter applications, having been used for 2 yr in a large-scale inorganic chemical plant in Germany (see also Section 6.3.3). Bazeev *et al.* (1965) found that if aerosols formed by the combustion of coal are filtered through feed coal contained in a precondenser chamber, tar is condensed on the coal particles and dust is absorbed on the tarry coal particles; the result is an improved semicoke useful in iron production. Raichle and John (1965) review dust control in the chemical industry and briefly mention gravel filters cleaned by reverse flow and shaking (see Section 6.3.3). Kuypers (1966) discusses heat-absorption tests and the loss of air pressure as a function of the amount of air passing through filters of various sizes of crushed stone. Haupt (1966) presents a curve for 0.45-mm-diam sand showing relative permeability (max permeability = 1) as a function of velocity of flow rate (m/min). Lühr (1966) designed an apparatus (see Section 7.5) consisting of several narrow filter cells arranged in parallel in one or more chambers; dust-laden gases are sucked downward through layers of sand or kisselguhr, which are subsequently cleaned by upflow agitation of the cleaning gas. A 1967 extension of the patent describes "a plurality of filter cells arranged in a plurality of vertically spaced, horizontally extending rows," allowing for greater filter area and an increased rate of filtration without a proportional increase in installation height. Squires' (1967) device allows gases to be treated by contact with granular solids in coal gasifications, catalytic contacting, gas absorption, and filtration of particulate matter. The gas is passed through perforated walls and a vertical column of sand supported by horizontal louvers. Williams *et al.* (1967) conducted an electron-photomicrographic study of sand-grain surfaces and found that adhering traces of clay materials were exceedingly difficult to remove. He also found that any or all of five surface textures may be present on any sand grain. Iinoya and Orr (1968) briefly mention sand, coke, and gravel beds and classify aggregate filter beds as fixed, dynamic or continually regenerated, fluidized, and nearly fluidized.

1.2.2 Deep-bed Sand Filters for the Removal of Radioactive Aerosols from Off-gas Streams of Reactor Fuel Reprocessing Plants

The removal of radioactive aerosols by sand filtration was first conceived by Lapple (1948a) as an expedient for eliminating active dusts and mists but not vapors from the 200 Area processing stacks at Hanford. An interim report for June 22 to August 2, 1948 (ibid.) discusses the philosophy and initial experimentation that led to full-scale specifications. Active particles to be removed from the gas stream had 0.5-2.0-μm diameters at a concentration of <0.01 grain/1000 ft^3; total atmospheric dust concentration was $\sim$1 grain/1000 ft^3. Tests with a 2-ft-deep bed of 20-40 mesh sand gave $>99\%$ collection at superficial gas velocities up to 10 ft/min. In comparison, a scrubber containing 4 ft of 1/2-in. wetted Berl saddles and 1 ft of 1/2-in. dry Berl saddles plus a cyclone entrainment separator gave collection efficiencies of $<98\%$ and usually $<90\%$. The scrubber project was dropped, and an intensive effort was made to determine collection efficiency, pressure drop, particle concentration, and the effects of acids and caustics on laboratory-scale sand filters. Plans for full-scale sand filters required the consideration of size, air distribution, sand and aggregate layer specifications, filter life, air-handling capacity, structural details, the possibility of removing radioactive iodine, and applicability to the Redox process.

Lapple's report (1948b) for August 2 to October 11, 1948, stated that both West and East Area sand filters were well under way, having been expedited by changes in aggregate specifications. Recommendations included loading finer grains of sand pneumatically (based on the results of compaction studies) and shipping in boxcar loads for economic reasons, as well as designing installations having excess static pressure potential and flanged connection ports that would allow future additions. Sketches of systems that eliminate the need for distributor blocks and/or supporting aggregate are also given (see Section 2.2). Concurrent laboratory tests indicated that collection efficiency increased with increased filter depth and/or finer sand-grain size. Irregularly grained sands such as Hanford sand gave better collection efficiencies; increased gas velocity lowered collection efficiency. A rough approximation was derived as follows:

$$n = 1 - \exp(-KL^{1/2}/V^{1/3}D^{4/3}),$$

where

n = fractional collection efficiency on an activity basis,
L = depth of fine sand, ft,
V = superficial gas velocity, ft/min,
D = average sand grain diameter, in.,

and

K = proportionality factor.

Sand permeability tests showed that intense vibration and the extreme compaction that would result could almost double the pressure drop.

A progress report by Stainken (1949) for September 1, 1948 to January 1949, also summarizes the data on laboratory-scale columns of 1-4-ft bed depths of $\sim$0.020-in. (20-40 mesh) sand, which have collection efficiencies of 91.6-99.9%. Four types of sand tested in 2-ft beds with 6-ft/min superficial gas velocity gave collection efficiencies

of 99.38-99.93%. Sand filters for West and East Plants were put into operation in October 1948. Their inside dimensions are 46 by 108 ft with 8-1/2 ft total depth of sand and aggregate. The West Area unit contains 24 in. of 20-40 mesh sand, the gas inlet runs along one side, and distribution is through a layer of concrete construction blocks below the coarsest aggregate (2-3 in.). The unit is operated under negative pressure, and the average air flow is 24,500 cfm with 4.2-in. water pressure drop and 99.6-99.7% collection efficiency. The East Area unit filter contains 36 in. of 20-40 mesh sand, and the gas inlet is centrally located in a bed of tile filter blocks. The average differential pressure is 7.3 in. water; the air flow is 26,300 cfm, and the collection efficiency is 99.8-99.9%. Initial tests with fiberglass filters indicated that removal efficiencies were higher at higher superficial velocities and with less space required than with sand. Tests indicated a need for filtering dissolver off-gases through either a sand filter or a fiberglass filter.

Work (1948) clearly summarizes the development of sand beds at Hanford by Lapple and others for this period.

Lapple (1949b) discusses startup of Hanford sand filters in an interim report for October 12, 1948 to January 24, 1949. Passage through the sand filters reduced the stack effluent activity by only a factor of 10, probably because of "recontamination" of the effluent by dissolver off-gases mixed with the sand-filter effluent gases. Data on daily performance of sand filters are given; collection efficiency was measured by sampling main ventilation gases, upstream and downstream from the sand filters, through CWS Type 6 filter papers. Suggestions include checking out the system with a foreign tracer, making periodic incremental pressure-drop measurements to note any clogging tendencies, considering the purchase of a Hersey filter or a Cottrell precipitator, and continuing the in-depth studies of graded fiberglass filter beds as possible future replacements for sand filters. The sand-filter program was considered completed by Lapple, who predicted a future trend toward fiberglass filters.

Lapple (1949b) ascribed the "recontamination" of air cleaned by sand filters to dissolver off-gases bled into the base of the stack. Initial composition of this air may be >10% nitrogen oxides and iodine as vapor or salts, and metallic salt entrainment may be ~2 lb/day with a dust or solids concentration of 50-100 grains/1000 cu ft, 90% of which can be removed in a water scrubber. Consideration was given to discharging the dissolver gases into the sand filter, but large amounts of nitric oxide and steam in the dissolver gases made this undesirable. It was suggested that dissolver off-gases not be passed through the scrubber but through a separate fiberglass filter consisting of a 2-ft thickness of No. 55 fine Fiberglas supported by coarser layers and operating at ~3 ft/min with an allowable 5-in. water pressure drop; the scrubber would be left in place on a standby basis.

The first brief mention of the Hanford sand filters in the journal literature occurs in a review article, *Waste Disposal Symposium*, in Nucleonics (March 1949); the Kellex Corporation (1949) evaluated the efficiency of a sand filter of ~2-ft diameter with a 24-in. depth of AGS crushed flint (30-40 mesh) as a basis for comparing the sand filter with other types of equipment for the removal of radioactive particles. A 98.5% efficiency for the sand filter at a superficial gas velocity of 9 ft/min using a methylene blue aerosol was of the same order of magnitude as had been obtained in the Hanford tests.

Blasewitz (1949) reported that the Hanford filters were operated at ~5-ft/min upflow and collection efficiencies of 99.8% (East Area) and 99.4% (West Area) after 1 yr in service. Traverse measurements with an ionization chamber showed that most of the activity had been deposited in the coarser strata below the Type G (20-40 mesh) sand layer, with little penetration beyond 1 ft into the Type G layer. Other provisions were made for removing fission products from dissolver off-gases, which were evolved at flow rates of 20-200 ft^3/min and contained high concentrations of ^{131}I during metal dissolution periods and contained other high-beta particulates during periods between dissolutions. These off-gases were passed through reactors (of silver nitrate-coated Berl saddles) to remove 99.9% of the iodine and through a fiberglass bed to remove 99.95-99.99% of other fission products.

Blasewitz *et al.* (1951), developing fiberglass filters for aerosols, used laboratory sand filters (see Section 7.0) patterned after those used at Hanford as a basis for comparison studies in life-expectancy tests. As discussed in Section 5, the life of the filter was determined by the pressure drop at the 2-in. layer that includes the interface of Type IV sand (4-8 mesh) and Type V sand (8-20 mesh). When fiberglass filters were being evaluated, the collection efficiency for the full-scale sand-bed filters they were proposed to replace had been 99.7% for 2-1/2 yr with no maintenance.

Lapple (1954) compared sand deep-bed filters and glass fiber deep-bed filters with respect to principles of operation, design, cost, and performance (see Section 8.1.1.1). A sand filter 85 by 85 by 14 ft, handling 35,000 cfm at a superficial gas velocity of 6 ft/min and with 99.7% collection efficiency, would initially cost $5.57/cfm; a fiberglass filter of equal capacity, 28 by 70 by 9 ft, with 25 ft/min superficial velocity and 99.99% collection efficiency, would cost $2.86/cfm. Life expectancy was estimated to be >5 yr for a sand filter and >10 yr for a fiberglass filter. Blasewitz (1954a) reviewed the dissolver off-gas filtration program in which a silver nitrate reactor and Fiberglas filter were developed for iodine and particulate-matter removal. The substitute filter medium had more desirable properties for the given application than the already successful sand filters at Hanford. A fiberglass filter 2-1/2 by 5-1/2 by 4.3 ft, in conjunction with a silver nitrate reactor, operated at

20 ft/min superficial gas velocity with a 4-in. pressure drop and a 99.99% collection efficiency.

Coleman and Silverman (1954) briefly mention sand filters in their review on control of radioactive airborne wastes. Zahn (1953) considers the problem of fiberglass or sand filters for the Purex exhaust ventilation system. The first sand filters were installed on ventilation systems of "B" and "T" Bismuth Phosphate Plants in the Fall of 1948. In the Redox plant, fiberglass high-efficiency filters were installed on separate vessel vent systems and a sand filter was installed on the main ventilation air stream. Previous studies by Blasewitz (1951) indicated that fiberglass has certain advantages over sand-filter beds; conclusions in this study (Zahn 1953) indicated that the use of fiberglass would reduce the total cost of the project $520,000, give an initial pressure drop 3 in. less than that for sand, give a collection efficiency of 99.9% as compared with 99.5% for sand, and require a considerably smaller plot area. Detailed cost estimates included in the report compare sand to fiberglass filters; total cost estimates were $900,000 and $382,000, respectively.

Clark (1954) reports the use at Savannah River of a 7-ft sand-filter bed that operated at 99.7% collection efficiency; 60% of the total stack gases pass through the bed—first through a clay-tile distribution system, then upward through layers of increasingly finer sand, and finally through two holddown layers (total thickness: 12 in.) on top of the main layer to prevent mounding. Blasewitz (1954b) reviews air-cleaning operations at Hanford and describes proposed filters for the new Purex Plant as follows: A standby filter of Fiberglas for emergencies, which would effect 99% decontamination, would cost (installed) ~$100,000; a main line, deep-bed fibrous filter, which would effect 99% decontamination, would cost $250,000; the same type of system but with 99.99% removal efficiency is estimated to cost $375,000; a main-line sand filter is estimated to cost $750,000. A capacity of 100,000 cfm is assumed in all cases.

Another review by Blasewitz and Judson (1955) and a final report of earlier research (Blasewitz *et al.*, 1951) consider the performance of glass-fiber filters designed to operate at higher superficial air velocity, lower flow resistance, and greater efficiency and life expectancy than the sand filters then in current use at Hanford. Glass-fiber filters have collection efficiencies as great as 99.99%, compared with 99.7% for sand.

Palmer (1956), reviewing air-cleaning experiences at Hanford, commented on the costly construction of deep sand beds with respect to the large excavations and heavy concrete required and noted that large areas are required to keep the gas velocity at a minimum so that fluidization of the sand layers does not occur. Although present beds are operating efficiently with no maintenance, these beds will have to be abandoned once they become useless.

Davis (1958) analyzed data of the Redox sand filter with respect to sharp increases in activity in the air entering the sand filter in July 1954 and November 1957, as compared with the normal activity over a 4-yr period. (Failure of an oxidizer vessel and its subsequent removal from a cell were responsible for the activity increasing from about 1 to 44 Ci/day.) Traverse measurements of activity in the bed indicated a downward trend in activity in early 1958; activity values plotted near the interface of the E and F layers, ~42 in. from the bottom of the filter, provided an indication of the total activity in the filter bed (see Section 8.1.1).

Blasewitz and Schmidt (1959) summarize requirements for process air filters and experience at Hanford as follows: (1) collection efficiency of 99.99% for submicron particles; (2) minimum initial flow resistance; (3) minimum maintenance; (4) life expectancy of several years; and (5) containment of collected radioactive materials so that they cause no subsequent disposal problem. The underground sand filters, consisting of successively finer layers of sand and equipped with suitable air distributors and ductwork, operated satisfactorily for up to 8 yr with 99.7% efficiency. The latter efficiency is not sufficient for the more highly contaminated gas streams. All other criteria are met by the sand filters in use.

Silverman (1960), considering *Economic Aspects of Air and Gas Cleaning for Nuclear Energy Processes*, compares the installed cost of a sand bed with that of fiberglass-bed filters chosen for use in newer installations. He notes that in addition to the lower cost of fiberglass beds, their higher void volume and lower resistance allows a gas velocity over four times that possible with sand.

Rodger (1961) briefly mentions that sand filters are more resistant to high temperatures and corrosive conditions than the fibrous filters favored at the time of writing. Mawson (1965), in discussing treatment of gaseous effluents, refers briefly to Hanford deep-bed filters of sand and fiberglass. First (1968) gives a good historical review of air filters in general and notes that large filter beds of graded layers of sand and gravel ~10 ft deep had been operated 20 yr at Hanford and 13 yr at Savannah River without servicing or replacement—an important advantage when intensely radioactive material is being collected. However, higher airflow resistance, lower efficiency of activity retention, difficulty in final disposal when the bed is no longer functional, and higher initial cost have resulted in little current interest in sand filters. A 5 ft, 4-in.-deep fiberglass filter at Hanford was operated with lower air-resistance and more efficiency than the sand filters for 10 yr before becoming plugged with NH_4Cl. A discussion of First's paper (First, 1968, pp. 142-147) includes comments by Schmidt that although considerable engineering effort went into developing the sand filters, Hanford believes that fiberglass is superior since an equivalent unit can be constructed for two-thirds the cost, with one-half the pressure drop, with the activity release smaller by a

factor of 5, and with equal or twice the filter life. First referred to excellent reviews of sand filters by Lapple (1954) and of glass-fiber filters by Blasewitz (1954a), which included cost estimates. A comment by Kessie was that the plans of GE Midwest Fuel Reprocessing Plant to use a sand-bed filter because of its chemical, heat, and shock-wave resistance may have significant future implications. First believed that a sand filter has more restricted applications than does a high-efficiency filter.

Sykes and Harper (1968a, 1968b) reported on the design and operation of the 100 by 240 by 8-ft sand-bed filter at the Savannah River Plant. Exhaust air from two large fuel-reprocessing "canyon" buildings passes through a dehumidifier, heater, and fiberglass filter before passing through the sand filter and out a 200-ft stack. Collection efficiency is >99%, and the increases in differential pressure after 13 yr of operation are acceptable. Activity has penetrated only to the 30-50 (smallest) mesh sand, and gamma activity is now estimated to be ~1000 Ci/bed. Airflow ranges from 100,000 to 130,000 cfm with an almost constant superficial gas velocity of 4.7 ft/min. Increased differential pressure is attributed to ground-water leakage, with some permanent compaction of the bed and dust accumulation. Experience in the operation of this facility is reported in more detail in Section 8.1.2.

1.2.3 Other Studies and Applications of Sand or Granular Filters for Removal of Radioactive Aerosols

Other studies during the past two decades in the atomic-energy field with respect to filtration of radioactive aerosols by sand or other granular media include the work at Oak Ridge begun by Struxness *et al.* (1954). The problem of evolution of radioactive aerosols resulting from the breakup of bubbles at the surface of boiling liquids led to the consideration of sand filters for the removal of entrained aerosols. A 5-in.-thick, 4-in.-diam column of 0.007-in. median-diameter river sand was used; aerosol particle radii were ~0.1-0.4 μm. Studies of penetration as a function of superficial gas velocity and of penetration as a function of particle size indicated the existence of an aerosol size that had maximum penetration through a sand bed. In dry sand with a superficial linear gas flow of 0.4 ft/min, the decontamination factor for the most penetrating particle size was $>10^3$.

Thomas and Yoder (1956a) sought to determine the aerosol size that would have maximum penetration through sand and fiberglass. Tests showed maximum penetration for particles with a 0.25- to 0.5-μm radius, depending on the face velocity and the size of the sand granules. Rough irregular sands are more efficient for aerosol removal than spherical sand grains, and downflow filtration is more efficient than upflow for large particle sizes and low gas velocities.

Empson *et al.* (1956) compared three types of sand for the relationship of size, penetration, and upflow vs downflow filtration. They also studied aerosol penetration as a function of velocity.

Thomas and Yoder (1956b) gave another presentation of their data (1956a). Thomas and Yoder (1956c) also studied penetration of 0.1-1-μm-radius DOP aerosol through an 89-cm column of lead shot (~1.5-mm-diam shot). A plot of percent penetration as a function of aerosol radius (in μm) showed that an aerosol size for maximum penetration exists, 0.25- to 0.40-μm radius, depending upon conditions. Polystyrene microspheres of similar density and size were used to confirm the DOP calibration curve; charges were removed from the polystyrene aerosol by passing it over 1 mCi of ^{32}P before the run.

Yoder and Empson (1958a) designed a multibed (sand, soda lime, charcoal) low-velocity air cleaner to decontaminate the off-gases from radioactive wastes fixed in a sintered clinker. Dry sand effectively filtered the particulates, the efficiency increasing exponentially with depth of bed. For very moist aerosols, water that condensed in the filter voids in the lower few inches of sand could be drained into a sump below; ^{106}Ru was effectively removed in the condensate. The bed of soda lime removed oxides of nitrogen and trapped iodine at the sand-soda lime interface. Activated carbon removed any traces of iodine and reduced traces of nitrogen oxides to <1 ppm nitrites. At 0.1-cm/sec air velocity, 99.995% of all particulates and fission gases were removed, except xenon and krypton. Yoder and Empson (1958b) gave a reiteration of the multibed low-velocity air cleaner, which is 9 cm in diameter and contains, from bottom to top: 1200 cc wet sand, 4000 cc dry sand, 1200 cc soda lime, and 600 cc charcoal with a flow rate of 500 cc/min.

Thornburg (1958) considered methods for remote removal of sand from a filter highly contaminated with radioactivity—a water-eductor method, a pressurized-vessel method, and a steam-jet method. Only the latter appeared practical, and optimum conditions were determined for its use.

Glassmire (1956) discussed air-cleaning activities at Los Alamos, which included a study of small-capacity sand filters of ground volcanic tuff. Eight-in.-square filters with 1-4-in. beds of 12-20 mesh ground tuff gave excellent collection efficiencies for 5-40-μm particles, poorer collection efficiency for 2-3-μm particles, and apparently increased collection efficiency in the <1-μm range. Tests were made with heavy metallic contaminants on both wet and dry filters. Tuff is suggested as a good roughing filter.

Smith (1963), in a chapter on "Filtration of Radioactive Particulates," dismisses sand filters in one sentence, but dwells upon fibrous filters at some length. Hauptverband der Gewerblichen Berufsgenossenschaften, e.V. Staubforschungs Institut, Bonn (1961), mentions the need for structural elements that will provide good heat conduction to the outside so that heat generated by radioactivity

trapped in a deep-bed filter can be dissipated. Cooling of filter housings is also suggested.

Stephenson (1963) reports on the testing of a German sand filter designed to protect a shelter from the hot blast of a nuclear explosion. (Test results are reported in detail in Section 6.) A model shelter (a steel tank) connected to an air-blast device through an 8-in.-diam sand filter was constructed. Compressed air was used to simulate the nuclear blasts, and the filter was reasonably effective in attenuating overpressures of 100 psi of 2-sec duration. Air flows of 4-cfm/sq ft filter area for 36-in. sand depth, 6 cfm for 24-in. depth, and 12 cfm for 12-in. depth were obtained with a 1-in. water-gauge pressure drop. When the filter was subjected to blasts of hot pressurized air, the sand was observed to be a good heat absorber capable of maintaining the outlet air temperature at an acceptable level.

Glueckauf *et al.* (1964) used a filter bed of glass-like solid bodies (75 wt % SiO_2, 15 wt % K_2O, and 10 wt % CaO) located outside a reactor core to remove fission-product metal vapors from the gas coolant stream before it reached the heat exchangers. The filter material can be in the form of rings, rods, tubes, or beads stable at >700°C; a bed must have sufficient capacity to last for the period between reactor shutdowns. Glueckauf *et al.* (1965) improved the filter bed, heating it to minimize heat losses from the coolant gas to the filter bed and creating a pressure drop in the filter about equal to that in the reactor (see Section 6.3.3).

Krupchatnikov (1966) mentions granular-bed filters consisting of sand, filings, rubber and viniplast crumbs, etc. (This filter is illustrated in Fig. 7.2.) Collection efficiencies may reach 99%. Resistance increases as the filters begin to clog. Periodic loosening of the filter packing with a rake-like device lowers the resistance; however, the packing eventually has to be replaced. Soluble deposits can be removed by washing or steaming the packing with live steam. Granular beds vary greatly in size and design. A low-output unit is illustrated in which air enters at top, is drawn through a granular bed, and is discharged at the bottom of the unit. The rake-like mechanism, manually rotated, periodically loosens and then levels the bed. Graphs show the resistance of rubber crumb (2-6 mm) as a function of specific load, layer thickness, and packing density.

First *et al.* (1965) report that the firing of nuclear-rocket engines evolves radioactive exhaust gases that must be cooled to ~250°F by the use of water sprays before decontamination. Among the concepts considered was confinement and decontamination of the moist gases by flow through underground tunnels and upward diffusion through deep layers of desert sand and sorbents laid down during backfilling of a rigid tunnel structure. To achieve a superficial face velocity of 10 ft/min with a 10-in. water-gauge back-pressure limit, a gas flow of 2,450,000 cfm at 250°F would require 245,000 ft^2 total bed surface. Total estimated cost was ~$800,000. Although possibly the cheapest method considered, this concept was given third priority because of the amount of development time and effort foreseen.

Van Zelm and Clarenburg (1966) made a literature search on the use of sand filters for shelters used for collective protection against explosions. Properties considered were: heat capacity; attenuating effect on shock waves; moisture capacity; and protective capacity for toxic vapors, aerosols, and fallout particles (see parts of Section 6). Sand filters were found to attenuate shock waves and to have temperature- and moisture-leveling effects and thus some control of climate in a shelter. They are also useful for collecting hydrolyzable gases and large aerosol fallout particles and can serve as the main filter for protection against the effects of nuclear explosions. They offer insufficient protection against chemical agents and must be used in conjunction with antiblast devices when used as prefilters to protect aerosol filters.

Cheever *et al.* (1966) tested a sand and gravel roof backed up by HEPA filters to serve as the accident filtration system (see also Section 8.2.1) for the Zero Power Plutonium Reactor (ZPPR) at Argonne National Laboratory's Idaho Division. Penetration of uranium and plutonium was 0.0004-0.02% through 30 in. of sand. With HEPA backup filters, plutonium fume penetration should not exceed 0.0001% after a reactor accident.

The purification system (Section 6.3.4) of Lofting and Burnette (1967) for the Public Service Company of Colorado (PSC) reactor includes a large bed of activated carbon operating at the helium coolant temperature of 750-800°F. Its primary function is to remove condensable fission products such as iodine, tellurium, and cesium; however, it is also expected to be somewhat effective as a filter for dust and aerosols in the process stream and especially for entrained carbon particles (which may be laden with many different fission-product metals).

A notice in *Atomic Energy Clearing House*, October 2, 1967, referred to a "Hearing on Issuance of a Provisional Construction Permit" for the General Electric Co. Midwest Fuel Recovery Plant (MFRP) at Morris, Ill. Included in the construction cost estimate were a sand filter and stack (including associated equipment) for 60,000 cu ft costing $400,000 out of a total of $14,420,000.

The Design and Analysis Midwest Fuel Recovery Plant (1966) report refers to a sand filter, through which all potentially radioactive gaseous wastes must pass before stack discharge. Based on the Hanford design of graded layers of sand, the expected collection efficiency of the filter is >99.97% for particles >10 μm. Summaries of system safeguards give the expected performance of the sand filter under normal, abnormal, and accident conditions. Amendment 3 (1967) to this report answers AEC staff questions concerning the construction, sand and gravel specifications, and possible effects of an earthquake upon

the sand filter. Supplement I (1969) postulates a design earthquake and calculates displacement with respect to the filter structure, filter material, and berm. (A more detailed discussion is presented in Section 8.2.3.)

Lawroski (1968) describes the ZPPR Facility as a split-table type critical assembly machine; i.e., the two halves of the core are slowly brought together to complete the core. The reinforced concrete reactor cell, 50 ft in diameter and 23 ft high, has a roof of graded layers of sand and gravel that constitutes a highly efficient particulate filter, resistant to high temperatures (see Section 8.2.1). The roof is supported on a catenary cable system, and its thickness varies from 16 ft at the edge to 21 ft at the center. The sand and gravel roof plus a backup containment structure of 288 AEC-type high-efficiency filters effect an overall airborne particulate attenuation of 10^6.

McFee and Sedlet (1968) report an investigation (see Section 8.2.1) made primarily to determine the ability of sand to remove plutonium fume. The work was done in connection with design of the sand roof to be used in the ANL Zero Power Plutonium Reactor containment system. A plasma torch was used to generate a Pu-U-Mo alloy fume, which was drawn through 6- and 30-in. depths of sand at 1-133 and 1-28 ft/min, respectively. Penetration of the 6-in. sand column was 0.08-0.57%; for the 30-in. column, penetrations were 0.004% at 28 ft/min and 0.019% at 5 ft/min; for 30-in. sand columns in series with a high-efficiency particulate filter, penetration was <0.0001%. Discrete particle sizes ranged from 0.02 to 4 μm, and their mean diameter was 0.07 μm.

Kato *et al.* (1968) report the addition of a confinement shell to enclose the existing blast-resistant reinforced-concrete ZPR-6 and -9 reactor cells and the addition of an emergency venting system for the cells consisting of a sand filter, two banks of HEPA filters, and a 46-m stack. These modifications (see Section 8.2.2) were necessary before plutonium fuel could be used in ZPR-6 and -9. In a design basis accident involving the ignition of 60 kg of plutonium, vaporization of 22 kg of sodium, and the production of 2.7×10^{20} fissions, it was postulated that the cell pressure would reach ~35 psia. The emergency venting system would prevent further pressure buildup in the cell and would limit the amount of plutonium reaching the atmosphere to not more than 6.2 mg.

2. FILTER-BED MATERIALS

The choice of filter-bed materials used in production-scale filters has been primarily influenced by local availability of materials. Small-scale tests have usually involved comparison of material from several sources with locally available material.

2.1 SHAPE FACTORS

Sand-particle variables are diameter, sphericity, and roughness. Diameter is always reported as derived from standard screen analysis. Sphericity has not been reported for the sands used in deep-bed filtration work. Sphericities of some typical sands and of geometric shapes are given in Table 2.1. Roughness has been considered in a qualitative way only with respect to pressure drop (Brown, 1950, p. 216), but is reported to be a more significant variable than pressure drop with respect to filtration.

2.2 SIZE OF SAND

The initial sand and aggregate specifications for the first Hanford filter are reproduced in Table 2.2 (Lapple, 1948a). The bottom six layers are primarily for air distribution and support of the fine sand layer, Type G. The 4-8 mesh top sand layer primarily protects the fine sand layer against bed erosion resulting from horizontal flow of air in the plenum chamber. To prevent erosion of this relatively coarse grade of sand, this horizontal airflow velocity should not exceed 10 ft/sec at any point. A 2-ft freeboard has been allowed for airflow above the top sand layer. Specifications for sand Types A to F are somewhat arbitrary and not critical. The specification for Type G sand is very critical from the standpoints of both collection efficiency and pressure drop.

Because of the size distribution of material from the sand pits being worked, some difficulty was experienced in meeting specifications for some of the aggregate grades. The initial specification of the first Hanford sand filter (West Area) was changed (Lapple, 1948b, p. 3; Work, 1948, p. 16) as follows:

Type A

Initial specification: 0% over 3 in.; less than 5% under 2 in.

Revised specification: 0% over 3-1/2 in.; less than 5% under 1-1/2 in.

TABLE 2.1. Sphericity[a] of Typical Sands[b] and Geometric Shapes

Sand Type	Shape	Sphericity
-	Sphere	1.00
Ottawa	Nearly spherical	0.95
-	Octahedron	0.85
Rounded grain	-	0.82
-	Cube	0.81
Average sand	-	0.75
Angular grain	-	0.73
-	Tetrahedron	0.67
Flint	Jagged	0.66
Wilcox	Jagged	0.60
Flint	Jagged flakes	0.43
-	Cylindrical fiber (L/D = 100)	0.28

[a]Surface area of a sphere having a volume equal to that of the particle, divided by the surface area of the particle (Brown, 1950, p. 212).

[b]Perry, 1950, p. 394.

TABLE 2.2. Initial Sand and Aggregate Specifications[a] for Hanford Filter (Lapple, 1948a, p. 17)

Identification[b]	Depth of Layer, in.	Nominal Size	Tolerances
Type E	12	4–8 mesh	Less than 5% on 4 U.S. mesh
			Less than 5% through 8 U.S. mesh
Type G	24	20–40 mesh	Less than 2% on 20 U.S. mesh
			30-50% cum. % between 20 and 30 U.S. mesh
			Less than 2% through 50 U.S. mesh
Type F	12	8–20 mesh	Less than 5% on 8 U.S. mesh
			Less than 5% through 20 U.S. mesh
Type E	12	4–8 mesh	Less than 5% on 4 U.S. mesh
			Less than 5% through 8 U.S. mesh
Type D	12	1/2 in.– 4 mesh	Less than 5% over 1/2 in.
			Less than 5% through 4 U.S. mesh
Type C	12	1–1/2 in.	Less than 5% over 1 in.
			Less than 5% under 1/2 in.
Type B	12	2–1 in.	Less than 5% over 2 in.
			Less than 5% under 1 in.
Type A	24	3–2 in.	0% over 3 in.
			Less than 5% under 2 in.

[a] All grades are to be reasonably free of silt, clay, and organic matter.
[b] Sand layers are listed top to bottom; airflow is bottom to top.

TABLE 2.3. Final Sand and Aggregate Specifications[a,b] for West Area Filter (T Plant)

Identification[c]	Depth of Layer, in.	Nominal Size	Tolerances
Type E (Top)	6	4–8 mesh	<1% on 3 U.S. mesh <40% on 4 U.S. mesh <7% through 8 U.S. mesh
Type G	24	20–40 mesh	<2% on 20 U.S. mesh 30–50% between 20–30 U.S. mesh <3% through 50 U.S. mesh[d]
Type F	12	8–20 mesh	<5% on 8 U.S. mesh <5% through 20 U.S. mesh
Type E	12	4–8 mesh	<1% on 3 U.S. mesh <40% on 4 U.S. mesh <7% through 8 U.S. mesh
Type D	12	1/2 in.– 4 mesh	<5% over 1/2 in. <5% through 4 U.S. mesh
Type C	12	1–1/2 in.	<5% over 1 in. <5% under 1/2 in.
Type B	12	2–1 in.	<5% over 2 in. <5% under 1 in.
Type A (Bottom)	12	3–2 in.	0% over 3-1/2 in. <5% under 1-1/2 in.

[a] All grades are to be reasonably free of silt, clay, and organic matter.
[b] Work (1948) p. 16.
[c] Sand layers are listed top to bottom; airflow is bottom to top.
[d] Changed from original 2% specification for expediency.

TABLE 2.4. Screen Analyses of Sands Tested (from Work, 1948, p. 28, and Lapple, 1948b, p. 22)

Screen Analysis Number	Sand Type	Cumulative Percent Larger Than Specified Size, weight basis														Avg Particle Diam[c] in.
		3[a] 0.265[b]	4[a] 0.187[b]	8[a] 0.0937[b]	10[a] 0.0787[b]	16[a] 0.0469[b]	20[a] 0.0331[b]	30[a] 0.0232[b]	40[a] 0.0165[b]	50[a] 0.0117[b]	60T[a] 0.0097[b]	80[a] 0.0070[b]	100[a] 0.0059[b]	150[a] 0.0041[b]	200T[a] 0.0029[b]	325[a] 0.0017[b]	
1	Hanford 4–8 mesh	-	0.00	98.74	99.63	99.74	99.81	99.88	99.92	-	99.96	-	-	-	-	-	0.14
2	Hanford 8–16 mesh	-	0.00	0.84	18.36	98.82	99.62	99.83	99.90	-	99.93	-	-	-	-	-	0.069
3	Hanford 16–20 mesh	-	0.00	0.36	0.50	29.05	99.53	100.00	-	-	-	-	-	-	-	-	0.044
4	Hanford 16–20 mesh	-	0.0	0.0	0.5	11.0	90.0	-	100.0	-	-	-	-	-	-	-	0.040
5	Hanford 20–40 mesh	-	0.00	0.10	0.13	0.26	4.09	45.16	94.12	-	99.83	-	-	-	-	-	0.022
6	Hanford 20–40 mesh	-	0.00	0.00	0.00	0.00	2.0	30.0	88.0	-	100.0	-	-	-	-	-	0.020
7	Hanford to 4 mesh	-	2.5	12.5	14.0	-	25.3	33.3	53.7	-	86.2	92.1	95.1	-	97.9	-	0.018
8	Hanford 4–30 mesh	-	2.9	18.2	20.0	30.5	42.2	61.5	94.3	-	99.8	-	-	-	-	-	0.027
9																	
10																	
11	Ottawa 20–30 mesh	-	0.00	0.00	0.00	0.00	0.57	99.32	99.91	-	99.98	-	-	-	-	-	0.028
12	Ottawa 20–30 mesh	-	-	-	-	-	0.35	98.95	100.0								0.028
13	Ottawa 20–30 mesh	-	-	-	-	-	0.2	98.8	99.9	-	100.0	-	-	-	-	-	0.028
14	Ottawa 20–30 mesh	-	-	-	-	-	0.4	98.3	99.9	-	100.0	-	-	-	-	-	0.028
15																	
16																-	
17	Ottawa 30–40 mesh	-	-	-	-	0.0	0.1	5.4	98.2	-	100.0	-	-	-	-	-	0.019
18	Ottawa 30–40 mesh	-	-	-	-	0.0	1.2	3.7	96.2	-	99.2	-	100.0	-	-	-	0.019
19	Ottawa 30–40 mesh	-	-	-	-	0.0	0.1	2.3	94.5	-	99.7	-	100.0	-	-	-	0.019
20	Ottawa 30–40 mesh	-	-	-	-	0.0	0.0	1.8	94.4	-	99.7	-	100.0	-	-	-	0.019
21																	
22																	
23	Eau Claire Type G	-	-	-	-	-	0.2	28.4	96.3	-	100.0	-	-	-	-	-	0.021
24																	
25																	
26	Monterey Type G	-	-	-	-	0.0	1.1	31.5	86.9	-	100.0	-	-	-	-	-	0.021
27																	
28																	
29	A.G.S. Flint 30–40 mesh	-	-	-	-	-	0.1	21.3	93.1	-	99.8	99.9	100.0	-	-	-	0.021
30																	
31																	

[a] U. S. Mesh.

[b] Aperture, in.

[c] Size corresponding to 50 cumulative weight percent.

Type E

Initial specification: less than 5% on 4 mesh; less than 5% through 8 mesh.

Revised specification: less than 1% on 3 mesh; less than 40% on 4 mesh; less than 7% through 8 mesh. The aggregate should be free of appreciable amounts of sand less than 16 mesh.

In addition, after the prepared aggregate was inspected, it was decided that the depth of Type A material could be reduced to 12 in. from the initially specified depth of 24 in., and this change was made. The top layer, previously specified as 12 in. of Type E, was changed to 6 in. of Type E aggregate. The final specifications are given in Table 2.3.

To ensure that the top layer of aggregate will not be shifted by the gas flow, 6 in. of Type C aggregate has been placed over the top layer of Type E aggregate in the region of the gas outlet duct. This layer extends across the entire width (48 ft) of the filter for a distance of 20 ft under the gas exit manifold.

The second Hanford sand filter (East Area) had the following aggregate specifications (Lapple, 1948b, p. 4; Work, 1948, p. 17):

Type A: (12-in. depth) less than 1% over 2-1/2 in.; less than 2% under 1-1/4 in.

Type B: (12-in. depth) less than 1% over 1-3/4 in.; less than 2% under 5/8 in.

Type C: (12-in. depth) less than 1% over 3/4 in.; less than 5% under 4 mesh; material to be free of appreciable quantities of sand finer than 8 mesh.

Type D: (eliminated).

Type E: (6-in. depth under Type F layer and 6-in. depth over Type G layer).

Type F: (12-in. depth) as originally specified in Table 2.2.

Type G: (24-in. depth) as originally specified in Table 2.2.

A 6-in. depth of Type C material was placed under the gas outlet duct for the East Area filter, as had been done for the West Area sand filter.

Type G: When ductwork became available, allowing series operation of the fans, depth was changed to 36 in. to gain greater filtration efficiency.

Screen analyses of the sands tested are given in Table 2.4 (Lapple, 1948a, p. 22; Work, 1948, p. 28).

3. BED STRUCTURES

Sand beds may be classified as fixed, moving, or fluidized.

3.1 FIXED BEDS

Fixed beds are generally employed where aerosol concentrations entering the bed are low and where the bed is expected to operate for a period of years with little or no maintenance. Examples of such beds are large fixed-bed sand filters of graded aggregate layers, increasing in fineness from the bottom to the top of the filter. The coarser aggregate serves as a support for the usual 24-36-in. layer of fine sand in the filter. Details of the bed structure of the Hanford sand filters (Lapple, 1948a, 1948b) are given in Section 2.2, and a cross-sectional diagram of the Savannah River Plant sand filters (Sykes and Harper, 1968) and laboratory test columns used by Blasewitz (1951) are given in Section 5. Section 7 also contains diagrams of typical fixed beds such as those of Solvay (1889), Krupchatnikov (1969), and Blasewitz *et al.* (1951), and Section 7.2 contains a sketch by Lapple (1948b, p. 21) which shows no supporting aggregate. A compound filter of wet sand, dry sand, soda lime, and charcoal (Yoder and Empson, 1958a, p. 86) is illustrated in Section 7.3. The aggregate layers of test columns used by Blasewitz *et al.* are given in Section 5 (Blasewitz *et al.*, 1951, Pt. 1, pp. 86, 88-89). Shown in Section 8.1.1.2 are specifications for a typical fiberglass filter with graded layers of increasingly finer fibers from bottom to top (Blasewitz *et al.*, 1951, Pt. 1, p. 121). The sand roof of the ZPPR is shown in detail (Lawroski, 1968, p. 49) in Section 8.2.1. The test- and full-scale sand filters designed for use in Zero Power Reactor-6 and -9 emergency ventilation system are illustrated (Kato *et al.*, 1968, pp. 2 and 138) in Section 8.2.2.

3.2 MOVING BEDS

Moving-bed filters have generally been designed for industrial use when the gases to be filtered have a high aerosol or dust content that would soon clog a fixed-bed filter. Several such devices employing (1) moving belts of sand or other granular material or (2) louvers, slats, etc. over which the sand falls are mentioned in the patent literature and are presented in Section 7.5. Clean sand or other granular filter material is continuously fed into the top of such a device, gases to be cleaned are allowed to flow through the moving bed, and soiled filter material is removed at the bottom for cleaning before return via an elevator device to the top hopper. Moving beds designed for high-temperature applications are discussed in Sections 6.3.3 and 6.3.4.

4. FILTRATION MECHANISMS

The aerosol collection process in filtration is readily described as collection by several different process mechanisms. The basis for differentiating individual process mechanisms is the type of particle force involved.

4.1 INTERCEPTION

Interception describes the mechanism whereby aerosol particles are collected on surfaces due to gas convection. When gas-drag forces on a particle completely dominate all other forces on the particle, such as inertia, gravity, diffusion, and electrostatic forces, the center of the particle tends to follow the normal flow lines of the gas. Particles on any flow line that passes within the particle radius of a surface will be caused to collide with that surface. The attractive Van der Waals' forces between the aerosol particle and the collecting surface become dominant at surface spacings of the order of 10 Å and cause the particle to become permanently attached to the collecting surface if the normal range of conditions for aerosol filtration is present.

When the flow channels are too small to allow aerosol particles to pass, collection is ensured, being referred to as complete interception or sieving. For large-scale aerosol filtration, this type of collection mechanism results in impractically high pressure drops and too low a capacity to collect aerosols without excessive plugging. Sieving is normally a significant mechanism when recovery or removal of collected material without destruction of the filter media is desired. Sieving is significant in membrane filters used primarily for aerosol sampling but is not normally significant in any large-scale high-efficiency aerosol-filtration application.

4.2 GRAVITATIONAL SETTLING

Gravitational force has a significant effect on aerosol collection for particle sizes down to at least 0.2-μm radius. This effect has been demonstrated experimentally by the observed decreased penetration for downflow compared with upflow in sand beds (Thomas and Yoder, 1956b, p. 548; Yoder and Empson, 1958b, p. 107; Yoder and Empson, 1958a, p. 87) and in a lead-shot bed (Thomas and Yoder, 1956c, p. 552). No correlation or theoretical basis for the gravitational effect was found in the literature. The effect can, however, be readily understood by considering the combined effect of interception and gravitational settling on a single isolated sphere. Interception alone will result in aerosol collection only on the upstream half of the sphere. A gravitational force in the direction of bulk flow will tend to increase collection due to settling across flow lines. This effect can be significant even when the bulk-flow velocity is much greater than the settling velocity because of the velocity decrease as the surface of the sphere is approached. Similarly, a reversed gravitational force will decrease the collection on the upstream half of the sphere but may promote collection on the downstream half of the sphere. For this latter case, there is a minimum settling velocity necessary to overcome the local gas-velocity component away from the collecting surface. There is no corresponding minimum settling velocity necessary to decrease the collection on the upstream half of the sphere. Therefore, there is a range of conditions for which a reversed gravitational force will reduce the net aerosol collection by the sphere.

4.3 DIFFUSION

Diffusion is the only mechanism of aerosol filtration that becomes increasingly effective with decreasing size of the aerosol. Diffusion of the aerosol particle is based on the theory of Brownian motion (Einstein, 1926), which accurately describes the motion of a particle. No work has been found which applies this theory to aerosol collection in packed beds.

4.4 IMPACTION

The impaction mechanism in filtration is based on the inertial force of the particle. The inertial force tends to move particles across the gas flow lines toward the collecting surface in regions where the flow is diverging upstream of a fixed boundary surface. Impaction is not normally significant at the flow rates usually used in continuously operating filter beds. It can become the most significant mechanism at high gas velocities in the range above 5-50 cm/sec.

4.5 FLOW

To calculate the individual or combined effect of the above mechanisms, it is necessary to estimate an average pore geometry and a corresponding gas velocity field inside the pore. Even for the most regular packing, it does not appear to be practical to reduce the flow geometry to a two-dimensional approximation such as is used in fibrous filters. The large number of variables involved in packed beds makes exact treatment difficult. The simple regular

systems can probably be arranged to have similar filtration performance to the more practical packed beds used in practice. The similarity of performance between regular and practical packed-bed geometries was demonstrated with respect to pressure-drop correlations (Brown *et al.*, 1950, p. 2155). For this case, of the 10 different regular packing arrangements of uniform-sized spheres that were tested, the rhombohedral blocked passage arrangement gave a pressure-drop correlation within the range of the experimental error (±15%) over a wide variety of random packed beds. An experimental demonstration that filtration mechanisms are similar will be required if a high reliance is to be placed on the theoretical approach outlined above. The literature on momentum transfer (pressure drop), heat transfer, and mass transfer in packed beds with single-phase flow is very extensive and was not surveyed in any detail for this report.

5. PRESSURE DROP

The pressure drop due to gas flow in packed beds has been extensively studied and reported in the literature. No attempt was made to survey this literature, and only a few of the reference texts were examined. A good introduction to the subject is given in Brown (1950, p. 210). The relatively large number of variables required to calculate pressure drop are the following.

Particle
- Diameter
- Sphericity (see Section 2.1)
- Roughness

Bed
- Porosity
- Depth
- Orientation

Gas
- Velocity
- Viscosity
- Density

Filtration will depend on these variables and others, including aerosol properties.

Except possibly for small-scale sand-bed filtration experiments using Ottawa sand, little information is available in the literature on particle sphericity. Particle roughness has not been reduced to a quantitative measure and it not an important variable for pressure drop except at very high Reynolds numbers. For filtration, it is expected to be a more significant variable at normal gas flow rates.

Porosity is frequently accurately reported for small-scale experiments, but not for the larger filter units. Porosity is normally the most sensitive variable; therefore its determination requires a high degree of accuracy.

Loading

The filter lifetime is determined by the increase in pressure drop and decrease in gas flow caused by collection of solids within the filter. The effect of loading on filter lifetime is a very sensitive function of aggregate distribution within the sand bed. Filter lifetime can be significantly reduced if solids collection is concentrated in small fractions of the filter depth. Uniform concentration of collected solids in the coarse aggregate layers upstream from the fine sand layer tends to give maximum filter lifetime. The tendency toward localized peaking of the collected concentration of solids tends to be self-aggravating, because the solids collected tend to increase the local collection efficiency, and the increase in local collection efficiency increases the local rate at which solids are collected.

Localized loading in deep-layered sand-bed filters is further aggravated by local decreases in porosity at interfaces between graded layers. The mixing of two different aggregate grades usually results in a lower void fraction at the interface than in either grade alone. The extent of reduction in void fraction depends on the aggregate characteristics and on the techniques used to charge the aggregate into the filter bed. Techniques for significantly increasing filter lifetime may be developed by additional experimental effort on loading effects.

Information on the internal distribution of collected material in the large sand-bed filters is obtained from gamma-radiation scans obtained with a detector located inside a pipe built into the filter during construction. A typical scan obtained with this type of detector is shown in Fig. 5.1 (Sykes and Harper, 1968). The resolution of this type of scan is limited because of the penetrating character of the hard gamma radiation.

The localized effect of loading is better resolved in laboratory tests using a methylene blue aerosol (Blasewitz *et al.*, 1951). Figure 5.2 shows the type and distribution of sand layers in a filter. Specifications of the sand and aggregate are given in Table 5.1. The high concentration of methylene blue at the interface of Type IV and Type V sand is shown in the distribution plot in Fig. 5.3. The total pressure drop across the filter and the pressure drop across the 2-in. layer that includes the interface of Types IV and V sands as a function of total input loading are shown in Fig. 5.4. The data (summarized in Table 5.2) indicate that the peak loading effect in the 2-in. layer that includes the interface between the Type IV and Type V sand layers increased the pressure drop by a factor of 100, whereas the pressure drop for the rest of the filter increased by a factor of 1.3. Probably, the effective layer thickness limiting the lifetime of this filter was considerably less than 2 in.

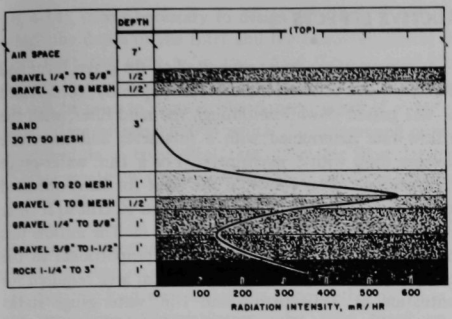


Fig. 5.1. Typical Radiation Intensity in a Sand Filter (Sykes and Harper, 1968).

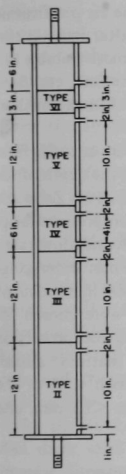


Fig. 5.2
Third Sand-filter Test Unit, Indicating Pressure-tap Locations (Blasewitz *et al.*, 1951).

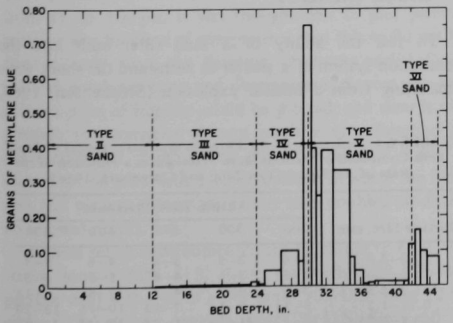


Fig. 5.3. Methylene Blue Distribution in the Second Sand-filter Test Unit (Blasewitz *et al.*, 1951).

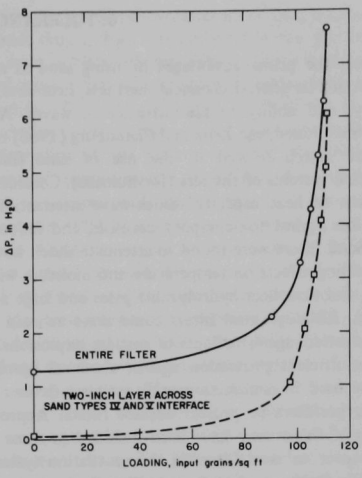


Fig. 5.4. Pressure-drop Increase due to Loading a Sand-bed Filter with Methylene Blue Smoke (Blasewitz *et al.*, 1951).

TABLE 5.1. Specifications of Aggregates[a] in the Test Sand Filters (Blasewitz *et al.*, 1951)

Type of Aggregate	Nominal Size	Tolerances
II	1-3/4–5/8 in.	<5% over 1-3/4 in. <5% under 5/8 in.
III	3/4 in.–4 mesh	<5% over 3/4 in. <5% through 4 U.S. mesh
IV	4–8 mesh	<1% on 3 U.S. mesh <40% on 4 U.S. mesh <7% through 8 U.S. mesh
V	8–20 mesh	<5% on 8 U.S. mesh <5% through 20 U.S. mesh
VI	20–40 mesh	<2% on 20 U.S. mesh 30–50% between 20 and 30 U.S. mesh <3% through 50 U.S. mesh

[a]All grades were reasonably free of silt, clay, and organic matter.

TABLE 5.2. Summary of Peak Loading Effects in Relation to Total Filter Effects (Blasewitz *et al.*, 1951)

	ΔP, in. H_2O		
	0 grains per sq ft	114.5 grains per sq ft	Loading Effect
Entire filter	1.29	7.65	6.36
Layer IV–V	0.06	6.05	5.99
Entire filter minus layer IV–V	1.23	1.60	0.37

6. TOLERANCE TO DESTRUCTIVE EFFECTS

Among the prime advantages of using sand as a filter medium are its general chemical inertness, heat-absorption capacity, and ability to attenuate shock waves. As previously mentioned, van Zelm and Clarenburg (1966) made a literature search related to the use of sand filters in ventilation systems of shelters (for humans). Consideration was given to heat capacity, shock-wave attenuation, and protection against toxic vapors, aerosols, and fallout particles. Sand filters were found to attenuate shock waves, to have leveling effects on temperature and moisture within a shelter, and to collect hydrolyzable gases and large aerosol particles. Although sand filters could serve as main filters for protection against effects of nuclear explosions, they offer insufficient protection against chemical agents and must be used in conjunction with antiblast devices when used as prefilters to protect aerosol filters. Appropriate sections of this survey have been included in some detail with respect to sand filters in the ventilation systems of protection shelters such as those in West Germany.

Subsections of this section related to ventilation flow characteristics under normal operating conditions, blast attenuation, and heat absorption of sand in a protecting shelter are taken from a report by Stephenson (1963) on work carried out by the U.S. Naval Civil Engineering Laboratory. Digestion and caking tests on various sands, reported by Lapple (1948a), are considered representative of the chemical effects from strong acids and caustic. The effects of moisture or wetting with respect to steam-injection tests are based on investigations by Lapple (1948a) and Work (1948). Various high-temperature devices and applications are mentioned that use sand and gravel filters or other granular materials such as coke, activated carbon, and dolomite. In subsequent sections of this report, it will also be noted that sand filters were chosen as parts of either operating or emergency ventilation systems in certain nuclear reactors and reprocessing plants for reactor fuels, the basis for their choice being the ability of sand filters to withstand sudden rises in temperature, pressure, moisture, and radioactive particulates without significant release of radioactive aerosols into the atmosphere.

6.1 VENTILATION FLOW CHARACTERISTICS– FLOW RATE VS PRESSURE DROP

Stephenson (1963, pp. 1-3) initially sought to determine airflow rates and pressure drops through a sand filter with respect to normal ventilation characteristics in a shelter. A 1-sq ft box was used that was deep enough to hold up to 40 in. of sand supported on a steel plate, a screen, and 2 in. of gravel. The sand conformed to specifications of the Artos Machinery Company: 80 to 90% from 1 to 3 mm, 5 to 15% from 0.2 to 1 mm, and up to 5% less than 0.2 mm.

A column of sand was supported on the gravel layer and vibrated with a concrete vibrator; subsequently, compressed air was passed downflow through the sand filter, with the airflow rate determined with a rotameter and the static pressure drop with a micrometer. For a 1-in. water-gauge static-pressure drop (possibly the limit for hand-operated equipment), airflow rates were 4, 6, and 12 cfm/sq ft filter area for sand depths of 36, 24, and 12 in. The airflow was found to be approximately inversely proportional to the sand-bed depth. The filter cross-sectional area required for ventilation at 3 cfm/person and 1-in. water-gauge static-pressure drop were also calculated. For 100 persons in a shelter, sand-filter depths of 12, 24, and 36 in. would require 25, 50, and 75 sq ft filter cross-sectional areas, respectively.

Sand filters were adopted as part of the air purification system in West German shelters in 1955 after investigators at Dräger laboratories showed sand to be more suitable as a filter material than cokes, earth, gravel, sawdust, etc. Sand filters have a lower resistance to airflow than earth filters (van Zelm and Clarenburg, 1966).

The resistance of or pressure drop in a sand filter depends upon the particle size of the sand, the depth of the sand layer, and the rate of airflow. Table 6.1 (van Zelm and Clarenburg, 1966, p. 9) summarizes data on pressure drops obtained with various sizes of sand at different flow rates. From these data, acceptable values of 20-mm water-gauge pressure drop at a volume flow rate of 600 liters/min/m^2 area through a fixed bed depth of 1 m were chosen for subsequent experiments with sand filters for protection shelters. The sand specifications provided that only a small fraction of the particles be <0.75 mm, with <5% of the particles <0.2 mm, <15% of the particles <1.0 mm, and >90% of the particles <3.0 mm.

6.2 PRESSURE–BLAST ATTENUATION OR SHOCK CAPACITY

To test the ability of a sand filter built into the ventilation system of a shelter to withstand the shock wave emanating from a nuclear explosion (Stephenson, 1963,

TABLE 6.1. Resistance to Air Flow (in mm water gauge) of Sand Beds Composed of Various Sieve Fractions as a Function of the Rate of Air Flow[a] (Van Zelm and Clarenburg, 1966)

Particle Size, mm	Airflow Rate, liters/min				
	200	300	375	500	600
2.0–3.0	2–4	3–5	3–6	4–6	5–7
1.5–2.0	2–5	3–6	4–6	5–7	6–8
1.2–1.5	3–6	4–7	4–7	7–8	9–11
0.75–1.2	5–11	7–12	7–12	10–18	13–20
0.5–0.75	15–17	21–24	21–24	29–37	33–46
<0.5	>120	-	-	-	-

[a]Rate of airflow through 1 m^3 sand (1 by 1 by 1 m).

pp. 4-14), it was necessary to design an adequate model in which the depth of the filter and the characteristics of the sand were the same as in the actual German sand-filter prototype developed after World War II. Since compressed air can be used to simulate the positive phase of a nuclear blast, a model was built in which the compressed air was contained in a large steel tank (the Air Blast Device), another steel tank (or plenum chamber) serving as a shelter. A sand filter connecting the two was tested at various overpressures. The cross-sectional area and volume of the plenum were scaled down to match the sand filter, while rise time, overpressure, and other quantities pertaining to the dynamic load were scaled the same in this model as in the prototype. All ventilation rates were based on a water-pressure drop of 1 in.

In the operation of the Air Blast Device, the tank is partially filled with water to control the volume of compressed air. After the tank is filled with air, an air-actuated plug valve is opened, allowing air to rush into the inlet tube. Pressure builds up on a Mylar diaphram, causing it to burst. The result is a sudden pressure rise on top of the sand and a restricted flow of air into the plenum. When the air-actuated plug valve opens, two relief valves also open, and the pressure on the sand drops quite rapidly. The pressure just above the sand peaks in 20-45 msec, decaying to near zero in 1-6 sec. The peak pressure is a function of the original supply-tank pressure. Decay time can be regulated by adjustment of the supply-tank water level and by partially opening two gate valves to control the rate of airflow from the tank. Pressure cells or strain gauges were located in the plenum and a few inches above the sand filter; rapid-response thermocouples were located above and below the sand and in the plenum. Signals from pressure cells and thermocouples were amplified and fed to an oscillograph.

In the first set of blast attenuation tests with an 8-in.-diam sand filter (Artos specifications) and a 2-sec impulse duration, plenum volumes were varied from 30 to 60 ft^3, filter depths from 12 to 36 in., and overpressures from 15 to 100 psi. It was thought best to plot plenum pressure as a function of overpressure, but this could not be done directly since the duration of shocks varied. Since impulse combines time and overpressure, plenum pressure as a function of impulse could be plotted, and then it was possible to determine plenum pressure as a function of overpressure at a prescribed duration time of 2 sec. A second set of tests with a 12-in. column in which the filter area and plenum volume were more than doubled produced no unusual results.

A third set of tests compared the resistance to blast of a coarse sand (100% U.S. Sieve 6-8 with 2.38-3.36-mm particle size) with that of a fine sand (90% U.S. Sieve 12-16 with 1.19-1.68-mm particle size; 5% U.S. Sieve 60 or smaller with particles 0.25 mm or less). The results showed marked differences in the ability of the sand samples to resist a blast. At 100-psi overpressure of 2-sec duration with fine sand, only a 3-psi rise occurred in the plenum; with coarse sand, a >9-psi rise was noted. Thus, a modest change in sand particle size can produce a sizable change in blast attenuation. For a sand filter to be used at higher overpressures such as 100 psi for 2-sec shock duration, careful grading of the sand is required. For lower overpressures of approximately 25 psi and 2-sec duration, a sand of commercial grade such as that from Artos Machinery Company (90% as large as 3 mm or as small as 1 mm) is adequate. Carefully graded sand costs about six times as much as Artos-type sand. Sand can only retard airflow, not exclude it; therefore, time duration is important in considering the blast-attenuation properties of sand. A filter should be pretested as a unit, or sand should be carefully graded and matched against control samples.

For minimum conditions of 3 cfm of fresh air per person, and 66 ft^3 of space per person, the Artos Sand Filter would give blast protection (maximum 5-psi pressure rise in shelter) to a shelter 3500 or more feet from ground zero of a 1-megaton burst; overpressure would be 100 psi for 1.4 sec. At 10,000 ft from ground zero in such a shelter, a 10-megaton burst would produce 50-psi overpressure of 2.8-sec duration.

6.3 THERMAL

6.3.1 Hot-blast Tests

In a field test with a nuclear blast of 100 psi, the air striking the sand filter of a shelter at maximum pressure would be at about 730°F, but then isentropical expansion would cause a temperature drop to about 200°F at the end of the positive phase of the blast.

Since peak overpressure temperatures in the blast-attenuation tests were lower than the theoretical values, equipment was designed to conduct a series of hot-blast tests with preheated pressurized air (Stephenson, 1963, pp. 15-17). The apparatus consisted of a 3.7-cu ft tank mounted horizontally and connected to the top of an 8-in. shock tube. Air in the tank was heated by four heaters controlled by a variable transformer. Thermocouples were mounted at several points in the sand filter located between the shock tube and plenum. There was a thermocouple in the plenum, and pressure cells were located at the top of the filter and on the plenum. The sand depth in the filter was 36 in., and the plenum volume was 45 ft^3.

Four tests were made with preheated air at 15-min intervals to record the temperature-gradient movement through the sand. All blasts approximated the pressure-decay curve; the air temperature dropped sharply when the air expanded from the hot tank, but dropped slowly after striking the sand. For an initial temperature in the hot-air tank of 668°F, a peak overpressure on the sand of 77.2 psi, and a blast duration of 1.85 sec, the temperature just above

the sand was 90°F before the shot, 369°F at a maximum, and 275°F at the end of the shot. After the tests, the temperature 2 in. below the sand surface was 260°F, but 6 in. below the surface it was only 83°F, and 24 in. below the surface it dropped from 63 to 61°F. It appears that heat from high-temperature air is absorbed in the first few inches of sand and that the air is cooled still further by expansion. Once the air temperature is lower than the sand temperature, no further cooling results. This is not an adiabatic process, but a process in which the air temperature is moderated by the sand, which has a large heat-storage capacity. A shelter with a 36-in. sand filter could probably afford protection from a blast of 100-psi overpressure at 730°F.

6.3.2 Controlled-temperature Ventilation Tests

If hot air is drawn into a buried sand filter, the sand (acting as moderator) can prevent high-temperature air from reaching the shelter. To be effective, the sand must absorb heat from the air, rejecting it to the adjacent soil or to cooler air that subsequently flows through the filter. Soils highly resistant to heat flow would cause the sand to retain the heat, which would slowly be carried into the shelter by cooler air. Soils of low resistance to heat flow would rapidly carry off the heat from the sand, supplementing its moderating ability.

The apparatus for the controlled-temperature ventilation tests (Stephenson, 1963, pp. 18-27) consisted of a 45-ft^3 tank with a compressed air inlet and an outlet allowing air to pass through an electric heater before entering an 8-in.-diam, 36-in.-deep sand filter. Thermocouples were placed upstream and downstream from the filter and at two points within the filter. The filter was encased in 1 in. of fiberglass insulation. Four tests were made at different airflow rates and inlet temperatures over 24-hr periods. The flow rates used, 1.3 and 3.5 cfm, correspond to static pressure drops of ~1 in. and 2.5 in. of water, respectively, across a 36-in. sand bed depth. Maximum temperature of the air entering the filter ranged from 115 to 380°F; maximum temperatures of air leaving the filter ranged from 70 to 105°F.

To determine how much heat the filter could transfer to surrounding soil, calculations were made using a formula by Ingersoll *et al.* (1951), for two different soils:

Soil	Thermal Conductivity, Btu/hr/sq ft/(deg F/ft)	Thermal Diffusivity, ft^2/hr
A	0.22	0.011
B	0.80	0.024

Table 6.2 (Stephenson, 1963, p. 20) indicates that sand is an excellent heat absorber, and that while soil A would not absorb the total heat dissipated to the atmosphere, soil B could easily absorb the total heat dissipated and more.

A sand filter contained in a large concrete vessel must be provided with a pipe grid, or its container must be long and narrow with much of its surface area in contact with the soil to disperse heat to the surrounding soil. Such filters for shelters are estimated to cost $4,000-18,000.

Another observation was that heated air entering a shelter ventilation system may contain carbon monoxide and various unknown materials resulting from fires caused by a nuclear blast. However, the fairly low thermal conductivity of dry sand would insulate the ventilation system from external heat, even when the ventilation system was not operating. Thus, in controlled-ventilation tests, sand displayed very good heat-absorption capabilities and much of the absorbed heat could be dissipated from a well-designed filter to certain types of surrounding soils.

TABLE 6.2. Results of 24-hr Controlled-temperature Ventilation Tests (Stephenson, 1963, p. 20)

1. Test	1	2	3	4
2. Flow rate, cfm	1.3	3.5	3.5	3.5
3. Duration of test, hr	24	24	24	24
4. Max temp of air entering, °F	210	115	195	380
5. Max temp of air leaving, °F	70	70	85	105
6. Mean temp of air entering, °F[a]	112	74	102.5	163.5
7. Mean temp of air leaving, °F[a]	64.5	60	71.2	83.3
8. Total heat entering filter via air, Btu[b]	1750	1710	4320	9400
9. Total heat leaving filter via air, Btu[c]	153	460	1470	2120
10. Residual heat in sand after test, Btu[d]	195	-97	136	390
11. Heat lost through pipe wall, Btu (item 8 minus items 9 and 10)	1402	1347	2714	6890
12. Capacity of soil A to absorb heat, Btu[e]	1375	501	1330	2860
13. Capacity of soil B to absorb heat, Btu[e]	4380	1580	4180	8980

[a] Mean temp equals datum temp plus the respective mean air-temp rise. Datum temp was 55°F for tests 2 and 3, and 60°F for tests 1 and 4. Mean air-temp rise in each case was computed from the area enclosed by the respective curve and datum line. Areas were measured with a planimeter.

[b] Based on mean temp rise of air entering.

[c] Based on mean temp rise of air leaving.

[d] Based on difference between sand temp at beginning and end of test.

[e] Based on a 3-ft length of 8-in.-diam steel pipe. Soil temp assumed to be 55°F, and pipe temp assumed to be the average of items 6 and 7.

6.3.3 High-temperature Sand and Gravel Filter Devices

Klärding (1921) patented a filter device for constantly purifying hot blast-furnace and generator gases that contain large quantities of dust without costly reduction in the temperature of the gases. Granular filtering material flows continuously from an upper hopper, downward through a main filter chamber, through a lower funnel onto a vibrating sieve for dust removal, and then onto a conveyor that returns the clean filter material to the upper feed hopper. Dusty gases are introduced at the side above the main filter bed, flow downward through the bed, and exit at the opposite side. Part of the cleaned gas is directed against the dust-laden filter material as it is shaken on the sieve to aid in removing the dust, which falls through the sieve.

Nordström (1922, 1924) devised an improved means of separating dust, smoke, and the like from gases in a cement-burning process, a process for manufacturing chloride of lime, or copper smelting. The gases are passed through a granular filtering material in a filter tower. A separate current of atmospheric air moves dust from the filtering material as it falls through a step-like bottom chamber; cleaned filter material is conveyed back to the top of the filter tower; the removed dusty matter may be returned to the original process or used for another purpose. The filter tower, located between a furnace and a chimney, consists of two concentric perforated walls with the filter material contained between them. Gases from the furnace enter the inner chamber, pass outward through the filter wall to an outer chamber connected to the chimney, and are discharged to the atmosphere in a purified state.

Thomson and Nisbet (1924) invented a filter for cleaning dust-laden gases from a blast furnace by allowing the gases to be drawn horizontally through a vertically downward-moving screen of suitable ballast material. Ballast is continuously fed into a V-shaped hopper at top, slips downward over metal slats arranged in louver fashion, and is conveyed by a worm extractor down a chute to a sloping metal screen at the bottom. The screen can be agitated to facilitate separation of dust from ballast, which is then conveyed to the top hopper by an elevator mechanism. Suggested ballast material includes granulated or coarsely powdered quartz, flint, or metallic fragments.

Lynch (1930) patented a filter designed to handle large volumes of air or gas at high temperatures. It consists of a thick bed of granular filter material falling downward into piles in separate chambers. Gas flows through the bed at a low rate, not exceeding 10 linear ft/sec, and discharges in a direction approximately opposite to the direction of filter material flow after passing downward and then upward through each chamber. Filter material is continuously cleaned, being carried by an endless conveyor to a rattler or other device for dust removal, and then is hoisted back to the feed chutes by an elevator with an endless-bucket conveyor therein.

Lynch (1936) described a granular filter consisting of a bed of gravel (1/2-1 in. in diameter) that is continuously withdrawn from the bottom of the filter, passed over a screen for dust removal, and returned to the top of the bed. Superficial gas velocity was approximately 3 ft/sec for beds 1-4 ft deep, and pressure drop was about 1 in. water. Units of steel, high-chromium steel, and brick have been used to filter gases having temperatures up to 850, 1500, and 2000°F, respectively.

Mercier and Ehlinger (1950) developed a filter using sand or other granular material to remove dust from hot gases issuing from a boiler firebox or from a boiler heated by gases under pressure. The filter is designed to handle gases of any temperature or pressure. In principle, a sand of suitable size and quality is arranged to provide small volumes, small depth of mass, and considerable surface area so that gases may pass through the filter without excessive pressure loss. Fine sand is held by walls formed by cone frustrums vertically aligned and concentrically disposed approximately opposite one another with conical surfaces tapering in opposite directions. For coarse sand (>4 mm), vertical layers are held between two grids or between two perforated cylindrical metal sheets. The filter unit is radially divided into cells and is rotated. Gases to be cleaned enter at the top of a container designed to withstand a high pressure (such as 150 kg/cm^2), zigzag through the sand filter, and exit at the bottom during one-half revolution of the filter. During the other half-revolution, sand and dust are emptied down a pipe to a rotating screen. Dust falls through the screen while the sand passes into a screw conveyor or similar device to be raised to the top of the unit for recycling. Continuous cleaning and reuse of the sand permits uninterrupted operation without loss of the heat the sand has acquired through contact with the hot gases.

Véron (1951) designed a sand filter for removing entrained dust from gases produced by the combustion of pulverized coal at high temperature and pressure and destined to feed a turbine. The filter is contained in a cylindrical body having a domed cap and conical bottom—a form suitable for high gas pressures. An inner lining able to withstand high temperature forms a cooling jacket, through which compressed air is circulated. Gas enters at the bottom of the filter and passes upward through stepped tiers of sand in multiple trays through a network of interconnecting channels and pipes. Clean gas then flows through a separate system of inner chambers between the trays, exiting at the bottom of the filter on the opposite side of the filter. When the sand becomes heavily dust-laden, as indicated by an increase in pressure drop, slide valves are opened individually, tier by tier, releasing the sand for cleaning by any suitable method, and then the sand is returned to the top of the filter. Sand was chosen as a readily available filter medium that can stand high

temperatures without damage or diminished filtering power.

Dennis *et al.* (1960), in designing an incinerator for disposal of low-level radioactive wastes from hospitals or biological laboratories, used an 8-in. layer of 1/4-in. gravel to screen out coarse particles before the gas passed through a 2-in. bed of slag wool, packed 6.5 lb/ft^3. This filter unit, with a 2.8-sq ft filter surface, was housed in half of a 55-gal drum located ~8 ft downstream from the incinerator. Gases exiting from the incinerator at 1600-1800°F were passed at negative pressure through a water-cooled condenser so that filtration gas temperatures were 200-800°F with a pressure drop of ~1 in. water. In one series of tests in which 900 lb of sawdust was burned, the pressure drop increased from 0.5 to 0.7 in. water with a 90-98% filter-collection efficiency on a weight basis. A 4-in.-deep sand seal, between the main burning chamber and the afterburner, reduced air leakage to <5% and allowed ready access for repair.

Strauss and Thring (1960) experimented with beds of coarse granules of refractory materials for filtering waste gases from open-hearth furnaces; preliminary investigations indicated that ~90% collection efficiency at 600-700°C with a pressure drop of <4 in. water gauge might be attained. Materials chosen were crushed high-temperature insulating brick, ~5/16 in. or 7 B.S. mesh; high-temperature fireclay refractories of finer mesh, 14-24 B.S. mesh; and two types of ceramic filter discs, 2-1/2 in. in diameter by 1/2 in. thick. The test filters with crushed refractory materials consisted of 2-in. pipe sections, the filter material being supported on stainless steel wire held between gaskets in flanges; ceramic discs were cemented with high-temperature cement in a thick hollowed-out flange in the 2-in. line. Experiments were run with a variety of bed thicknesses and gas flow rates. Collection efficiency tests were carried out on cold and preheated beds. Reverse-flow tests were made to determine if dust and fume could be blown back into the furnace; the rate of reverse flow was varied to determine the effect on rate of heat loss by the bed and also its regenerative capacity. The "life" of the filter was gauged as the time required for bed resistance to exceed 4 in. water with a single reversal under operating conditions. For short operations such as oxygen lancing, filtration measurements of dust concentration were timed over the entire period, but in extended processes, such as melting and refining, measurements were limited to periods based on a single reversal of the regenerators. For crushed firebricks (12-25 B.S. mesh) in a 1-in.-thick bed, the filter-collection was 45.0% efficiency with a gas velocity of ~1 ft/sec and a maximum pressure drop of 14 in. water gauge. The ceramic discs had a filter-bed collection efficiency of 57-76% with a gas velocity of 0.9 to 1.68 ft/sec and a pressure drop of 13.6 in. water gauge. Gas temperatures were 60-63°C.

The 5/16-in. B.S. or mesh crushed high-temperature insulating brick was the best of the materials tested. Filter-bed collection efficiencies of 59.3-96.3% were obtained with bed thicknesses of 1-10.5 in., average gas velocities of 1.19-3.35 ft/sec, and maximum pressure drops of 0.38-4.90 in. water gauge at gas temperatures of 230-520°C.

Further theoretical studies by Thring and Strauss (1963) considered the effect of high temperature on particle-collection mechanisms and compared the most promising collection methods—electrostatic precipitation, filtration by fine fibers, and refractory pebble-bed filters. A review and statistical analysis of the preceding data (Strauss and Thring, 1960) on crushed-brick bed filters showed that the most important factor in collection was inlet-particle concentration, an indication that particle agglomeration in the bed plays a highly significant role in collection. Increased mass flow rate of gas and increased temperature also increased collection, but to a lesser extent. When the temperature of the gases differs greatly from that of the bed, thermal precipitation plays a role, but other mechanisms are more important. A 9-in. filter bed with 400°C average temperature can preheat an incoming gas stream 160°C by a reversal of gas flow. A packed bed of this type could replace the classical regenerator in open hearths, requiring less space and decreasing fumes in the exit gases by more than 90%.

A report by Hauptverband der Gewerblichen Berufsgenossenschaften, e.V. Staubforschungsinstitut, Bonn (1963, p. 5), stresses the need of providing good heat conduction to the outside of a deep-bed filter for radioactive aerosols so that heat generated by radioactivity trapped within the filter is properly dissipated. Filter housing also should be cooled.

Goldman (1964) reports that gravel-bed filters have been used for several years in Germany as large-pore filters that are wear-resistant in high-temperature applications to 350°C. The theory of the collection process is given briefly. Prior to adoption of these filters, tests were made with various dusts, including coke dust in the off-gases from a coke-drying operation, phosphate dust, dust in the fumes from a carbide furnace, and dust in the waste gases from a mixture of phosphorescents. Crude gases contained 0.5-3 g of dust/Nm^3 (cubic meter at standard temperature and pressure); the purified gases contained 10-95 mg/Nm^3. Dust removal was in the range 93-97%, with pressure drops of 110-200 mm water gauge and flow rates of 4,000 to 70,000 m^3/hr. When the pressure drop became too high, the gravel was washed and the clean gravel returned to the bed for reuse. For high-density coarse particles (>10 mm), mass-inertia forces acted advantageously by impact deposition; however, fine aerosol dusts traversed the gravel bed without being secluded. When sublimed dust from volatile carbide came into contact with atmospheric moisture, it was converted immediately to lime dust and tended to coagulate, which aided its filtration. In addition to these test results, experiences with gravel filters in a large chemical

plant over a 2-yr period are reported.

Glueckauf *et al.* (1965) invented a filter of discrete "glass" bodies for removing long-lived fission-product metal vapors such as cesium, strontium, and barium from the coolant gas of a high-temperature, gas-cooled nuclear reactor. The filter of discrete "glass" bodies can be in the form of rings, rods, tubes, beads, or fibers able to withstand temperatures of 700-800°C. An example of its composition is 75 wt % silica, 15 wt % potassium oxide, and 10 wt % calcium oxide. Glasses based on oxides of potassium or cesium, iron, aluminum, calcium and/or silicon are suggested as preferable. Such "glasses" possess a high diffusion coefficient, allowing the fission products to diffuse through the entire mass of the material.

Contaminated coolant gas flows out of the reactor through the filters; clean gas from the filters flows to the heat exchangers, where the useful heat is given up. The gas is then piped back to the reactor. When the filter becomes "saturated," the coolant gas stream can be closed off and an auxiliary gas stream used to sweep collected fission products out of the filter and thus regenerate it. Pairs of filter beds allow alternate regeneration. Heating coils prevent undesirable heat losses from the filter bed, and pressure drop across the filter should be equal to that in the reactor. If a single bed of glass rods is placed in the reactor vessel neck, no problems of temperature variation or excessive pressure drop are encountered, but the filter must be replaced when "saturated."

Raichle and John (1965), reviewing dust control in the chemical industry, mention the use of gravel-bed filters at high temperatures. Packed-gravel filters generally have a low efficiency and do not always effect a satisfactory gas-dust content (<50 mg/m^3). They are cleaned by reverse gas flow or by shaking. Efficiency has been considerably improved by maintaining an even packing height during shaking. Also, changes in design and proper selection of materials have tended to eliminate initial difficulties in sealing. Gravel-bed filters can be used to treat hot exhaust gases from rotary barrel installations serving as dryers, coolers, or reactors. Fine dust accompanying the clean gas from cyclones attached to high-temperature fluidized-bed installations may be removed by passing the gas through a packed bed of heat-resistant gravel.

First *et al.* (1965) were concerned with radioactive exhaust gases evolved in the firing of nuclear-rocket engines. These gases must be cooled to ~250°F by the used of water sprays prior to decontamination. Among the concepts considered for confinement and decontamination of the gases were flow through underground tunnels and upward diffusion through deep layers of desert sand and sorbents laid down during backfilling of the rigid tunnel structure. For a superficial face velocity of 10 ft/min, 10-in. water-gauge back-pressure limit, and a gas flow of 2,450,000 ft^3/min at 250°F, a total bed surface of 245,000 ft^2 would be required.

Construction costs were estimated, based on the excavation of a tunnel 9,750 ft long, 16 ft wide, and 19 ft deep, totaling 57,500 yd^3; at $0.75/yd, the cost would be $43,000. The 16-ft-diam half-cylinders of perforated corrugated culvert sections required would cost ~$300,000, and the graded stone gravel and absorbents another $450,000. The ~$800,000 estimated total cost is considerably lower than estimates for other systems.

Although such an underground system would be out of the way, have tunnels large enough to allow the use of mechanized equipment for any repair or maintenance, and probably last for years, problems associated with explosion prevention would have to be resolved. All tunnels would have to be purged with nitrogen before and after each test to prevent the accumulation of explosive quantities of hydrogen. Burning the hydrogen would be a possible solution, but containment of the hydrogen flare would present a problem not yet solved.

This concept was given third priority because of the amount of development time and effort foreseen.

Kuypers (1966) made tests to determine the loss of air pressure as a function of the amount of air processed by filters containing stones of various sizes. Heat absorption by a stone filter from hot air passing through the filter was also determined. The size of the crushed stone has a definite effect on measured air resistance and maximum heat absorption, as shown by data and graphically plotted results. Porosity percentage also has an effect; the lowest porosity percentage correlated with the 5-10-mm stones.

A literature survey by van Zelm and Clarenburg (1966) of sand filters as related to protection in a shelter considered the following aspects: (a) heat capacity, (b) attenuating effect on shock waves, (c) moisture capacity, (d) protective capacity for toxic vapors, and (e) protective capacity for aerosol and fallout particles. A sand filter is capable of attenuating shock waves, controlling the climate in a shelter by its temperature- and moisture-leveling effects, collecting hydrolyzable gases and large aerosol particles from fallout, and thus protecting against the effects of nuclear explosions when used as a main filter. It does not give adequate protection against chemical agents. As a prefilter upstream from an aerosol filter, it must be protected with an antiblast device.

6.3.4 High-temperature Applications of Other Granular Filters Containing Coke, Activated Carbon, or Dolomite

Donaldson (1924) discussed two coke towers designed to remove dust from hot gases evolved in Herreshoff roasters in which crushed pyrites are burned. Gases entered at the bottom and flowed upward through a bed of 2-in.-gauge broken coke; clean gas exited above the coke bed at the top of the tower. A tower with a 2-ft^2 shaft containing a coke bed with a height of 3-4 ft above rill,

handled ~600 cfm of very dusty gas with an ~1-3/4-in. water-gauge loss of pressure. Coke could be replaced intermittently or continuously. Dirty coke was removed by shovel at the bottom and added to the smelter; clean coke was added at the top. No quantitative methods were employed for determining actual filter efficiency.

Egleson *et al.* (1954), discussing a moving coke-bed gas filter for dust removal at ambient temperatures, suggested that dust could be removed from a hot gas with a dry filter bed. A conventional mechanical hoisting device could return the hot coke to the top of the bed after the coke is screened to remove dust to facilitate hot dedusting and recirculation. Another advantage of dry dedusting is that it allows valuable dust to be recovered. Another filter medium that is as efficient as coke where heat recovery is desirable is 4-8 mesh broken silicon carbide; 4-8 mesh bauxite also shows promise. Both of the latter are rough porous materials, which tend to be more efficient than smooth, regular-shaped filter media.

Knapsack-Griesham Aktiengesellschaft of Koln, Germany (1960), patented a process and apparatus for purifying metal vapors by passing them through a loose, flowing, granular, inert filter medium such as coke or dolomite at a temperature above the condensation point of the pure material. This process is particularly applicable to magnesium vapor, but could also be used for zinc, cadmium, alkali metals, and alkaline earth metals.

Magnesium vapor formed at 1400°C by the reaction of magnesium oxide with a reductant (ferrosilicon, for example) in a furnace under reduced or normal pressure is impure, containing about 96.5 wt % Mg, 1 wt % Si, 0.1 wt % Fe, 0.5 wt % Ca, and 0.5 wt % Mn plus solids. Vapors enter near the top of a filter chamber 2.5 m high by 80-cm ID at ~25 m^3/hr, a pressure of ~30 mm Hg, and 1300°C. Concurrently, ~30 kg or 6 liters/hr of cold lump coke (10-15-mm diameter) passes downward, filtering the vapors; the vapors exit at a point near the middle of the chamber at a temperature of ~850°C, then flow into a condenser where the temperature drops from ~800 to 500°C. The composition of the purified vapor is 99.93 wt % Mg, 0.02 wt % Si, 0.001 wt % Fe, 0.01 wt % Ca, and 0.03 wt % Mn.

The entrained solids and condensed vapor impurities are removed on the coke, which leaves at the bottom of the chamber at 850°C. To prevent premature condensation or clogging within the chamber, a stream of hydrogen, nitrogen, or argon is passed into the top of the chamber and out with the purified vapors.

Dolomite (10-15-mm diameter) flowing at 60 kg/hr (60 liters/hr) could be substituted for coke as the filter medium for magnesium vapors. The purification system can also be designed so that the vapor flows countercurrently to the filter medium.

Bazeev *et al.* (1965) showed that aerosols formed by the combustion of coal in power-generation plants can be removed by filtering the aerosols through feed coal in a precondenser chamber. Tar is condensed on the coal particles, improving the semicoke formed; dust is absorbed on the tarry coal particles so that pure liquid condensate and gases are produced. Semicoke resulting from the process is suitable for iron production. Theoretical aspects of the proposed dust removal process were also considered.

Lofing and Burnette (1967) made a series of tests on the high-temperature filter-adsorber unit of the Public Service Company of Colorado (PSC) reactor. This unit consists of a large bed of activated carbon operated at 750-800°F (the helium coolant temperature) to remove condensable fission products such as iodine, tellurium, and cesium by adsorption and to filter out any dust or aerosols entrained in the process stream (particularly carbon dust that may be laden with absorbed fission-product metals). The series of experiments was designed to measure the penetration and distribution of (1) in situ generated dust particles, (2) externally generated dust particles, and (3) iodine vapor.

The test apparatus consisted of a stainless steel trap, 39 in. long with a 7/8-in. ID, heated by two clamshell furnaces. Uniform axial temperatures at the trap inlet were ensured by a preheated coil of 1/8-in. tubing; a water-cooled section at the column outlet prevented excessive heating downstream. Any particulates penetrating the column were collected by a high-pressure millipore filter unit (0.22-μm pore size) placed below the column. A circulator, a flowmeter, a bypass cleanup system, and assorted valves and fittings completed the circuit. The trap for the in situ tests was loaded with 5.7 g of 6-10 mesh activated charcoal, 0.45 g of charcoal tagged with ^{133}Ba (7.5-yr half-life), and an additional 185.9 g of activated charcoal. A small helium loop simulated reactor conditions of pressure, temperature, and gas velocity. The test trap was placed in the loop system, which was pressurized with helium; excessive gaseous impurities were removed from the gas stream by a liquid-nitrogen charcoal cleanup trap. Operating temperature was 800°F at 560 psig He pressure and a flow rate of 52 std liters/min. A bed scan was made through a 1/4-in. slit with a 3-in. NaI scintillation crystal and a 400-channel pulse-height analyzer, before gas flow was started and then after accumulated running times of 9, 45, 46, 56, and 213 days. On the 46th day, the trap was given 300 sharp raps with a hammer to produce a strong vibration. During the test period, there was little change from the initial scan. The greatest change occurred after the vibration test, which caused the carbon in the trap to settle with a 2-cm shift in the source activity peak. Increased ^{133}Ba activity, as well as carbon dust, appeared on the millipore test filter radioassays.

For the next test (for distribution or penetration of externally generated dust), carbon black was tagged with ^{85}Sr (64-day half-life). With the filter-absorber at full pressure, flow, and temperature, this carbon black dust was injected at the inlet. The apparatus was intermittently shut

down for gamma scans after 5, 34, 66, and 157 days of operation. A scan was also made after 63 days of running and 2 days after a vibration test of 300 sharp hammer blows. Plots of the activity profiles showed little change from the initial scan except after the vibration test, which broadened the activity distribution peak to about half the distance of the trap. The analytical results for the millipore filters indicated that the filter-adsorber is not an absolute filter for externally generated carbon aerosols, but becomes more effective with longer running; i.e., 1.3% of the carbon penetrated the bed soon after injection, an additional 5×10^{-4}%/day penetrated the bed as the run continued, and the rate was only 1.6×10^{-4}%/day for the last 89 days of the run. A conservative estimate is that 10% or less of the dust penetrates the reactor unit.

The final test was with iodine and involved first the sorption of 50 mg of elemental ^{131}I (8-day half-life) on 2 g of activated carbon at room temperature. The filter-adsorber unit was loaded with 10 g of activated carbon, the tagged carbon, and an additional gram of activated carbon to give a bed height of 100 cm. The run was made at 800°F, with 560-psig total pressure, and 25 std liters/min flow rate. The activity profiles for ^{131}I after 0, 7, and 64 days were plotted. The iodine peak moved about 2 cm in 7 days, but showed little movement thereafter, which may indicate that there was an initial settling of the bed.

Two final tests designed to simulate a major steam leak reactor accident involved injecting 2.5% and 50% water vapor in helium into the hot carbon bed for 15.5 hr at 1-atm pressure at equivalent gas velocities. No shift in the iodine peak resulted. Periodic removal of the millipore filters for ^{131}I analysis indicated a slight ^{131}I penetration which probably was related to a small amount of carbon dust noted on the filters.

The low iodine penetration of $\sim 10^{-6}$%/day may be related to dust generation by abrasion of the particles; however, the major part of the iodine stayed fixed near the bed inlet, perhaps held by reaction with alkali metal impurities.

Conclusions based on the result of the tests were as follows:

1. Minimal dust generation from the abrasion of coconut charcoal in a packed bed will be encountered unless there is severe vibration.

2. The PSC high-temperature carbon bed can filter entrained dust particles with an expected efficiency of at least 90%.

3. Absorption of iodine on carbon at 400°C is essentially irreversible; probably, iodine reacts with alkali metal impurities in the charcoal to form metal iodides.

6.4 CHEMICAL

Various sands being considered for the large Hanford sand filter beds were tested to determine their reaction with various chemical reagents. Absorption of organic vapors and various war gases are summarized, and chemical impregnation of sand is discussed briefly.

6.4.1 Digestion Tests

Digestion tests (Lapple, 1948a, pp. 7-9) were run to determine the solubility of Hanford and other sands in various reagents. Sand samples were screened through a 10-mesh sieve and boiled in a reagent for 24 hr under total reflux. The percent digested was calculated from weight loss. Results and reagents used are given in the table below (Lapple, 1948a, p. 9).

Reagent	Percent Digested, Sand from Pit No. 1 near 200 West Area Gate (Hanford)	Percent Digested, Pit near 200 Area Road (Hanford)
10% Sulfuric acid	13.2	8.5
10% Nitric acid	6.7	7.8
10% Sodium hydroxide	4.3	3.0
10% Phosphoric acid	6.9	8.2
1% Hydrofluoric acid	6.1	3.2
Moisture content	1.7	0.9

The digestion tests for Ottawa sand showed no appreciable attack with any of the reagents.

6.4.2 Caking Tests

Caking tests involved heating 80 cm^3 of sand in 500 cm^3 of reagent for 24 hr at 200°F. The sand was then qualitatively examined, filtered, dried, and reexamined. Ottawa sand showed no caking tendencies after heating in the various solutions except for some crustation of the sample treated with caustic and dried. White Bluffs sand, 16-20 mesh, had no tendency to cake in any of the solutions except slightly in the caustic; results for the dried samples are not available (Lapple, 1948a, p. 9).

Ottawa sand, being almost pure silica, had almost no chemical reaction with the reagents likely to be present in the applications. Also, the Hanford sand, which had notable reaction with the test reagents, would be present in so large a mass in a sand bed that any reagent entering it would have little chance of causing appreciable consolidation of the sand bed over a period of years (ibid., p. 19).

6.4.3 Adsorption Characteristics for Organic Vapors and War Gases

The ability of sand and various types of soil to adsorb several concentrations of carbon tetrachloride and tetrachloroethane was studied (van Zelm and Clarenburg, 1966,

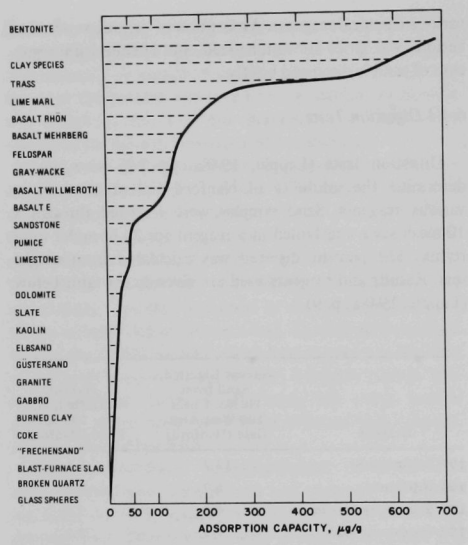


Fig. 6.1. The Order of Various Soils According to Their Adsorption Capacities (van Zelm and Clarenburg, 1966). 2.0 < particle size < 30 mm. Adsorption capacities were determined in dynamic tests with 5.12×10^{-4} g carbon tetrachloride/liter air; rel. humidity of gas-vapor mixture, 17%; depth of layer, 100 cm; air velocity, 27.5 cm/min; initial water content of adsorbent, 0.0%.

pp. 3-7). Figure 6.1 (ibid., p. 5) indicates that clay soils and very porous stones have the highest adsorption capacities while natural sands with high quartz content have little adsorption capacity. Protection time for an air-vapor mixture decreases slightly with an increase in relative humidity; thus, a river sand (2-3-mm grain diameter) showed a 24% decrease in protection time when the relative humidity rose from 17 to 100%. It was also noted that the amount of water present in the sand has a significant effect on the protection time from air-vapor mixtures. Protection time decreases with increasing water content. Sand has very little adsorption capacity for nonhydrolyzable gases such as carbon tetrachloride and tetrachloroethane, but has good protection or adsorption capacity for hydrolyzable gases like sarin, phosgene, and mustard gas. The absorption of nonhydrolyzable war gases such as chloropicrin, hydrocyanic acid, cyanogen chloride, bromo acetone, and arsine rapidly decreased with increased water content in the sand (van Zelm and Clarenburg, 1966, pp. 18-25).

6.4.4 Chemical Impregnation

Sand was impregnated with a few tenths of a percent by weight of sodium carbonate or sodium hydroxide to study the protection times against cyanogen chloride and hydrocyanic acid (van Zelm and Clarenburg, 1966, pp. 30-32). A 50-cm sand column with a 2.5% water content and 0.5% Na_2CO_3 gave protection against HCN for 56 min; 100-cm sand columns with a 2.5% water content and 0.6% NaOH gave a protection time of 30 hr against HCN and 12-hr protection against ClCN. However, sodium hydroxide impregnation reduces mustard-gas protection time from 22 to 1/2 hr for a 50-cm column of plain sand. Protection against sarin is expected to be improved by alkaline impregnation of the sand.

6.4.5 Possible Iodine Removal

Lapple (1948a, pp. 22-23) thought that experimentation should be done to determine if iodine could be absorbed on Hanford sand. If not, he suggested that a catalyst or catalyst-coated material of the same nominal size as the sand be used to absorb iodine and remove aerosols simultaneously in the sand filter, eliminating the need of a scrubber.

Later tests (Lapple, 1949a, pp. 2-3) seem to indicate that a sand filter could remove >95% of the iodine activity leaving the scrubber (an 8-in.-diam column with 4 ft of 1/2-in. wet Berl saddles, a 24-in. space, and 1 ft of dry Berl saddles). Ottawa sand used in the test filter is not known to have adsorptive affinity for vapors; therefore the iodine is assumed to have been present in particle form or dissolved in water droplets or as iodates. Hanford sand possibly has chemical-adsorption advantages, but these have not been tested. Recent tests suggested a high collection efficiency for iodine on silver-coated sand.

If iodine could be satisfactorily absorbed on Handford sand, the dissolver off-gases could be discharged directly into the large sand bed, but large amounts of nitric oxide vapors might be hazardous to the mechanical strength of the sand filter. Either compressed air or a fan should be used to exhaust the off-gases since the drainage capacity of the large sand bed may not be adequate for the large volumes of condensate formed when steam is used.

6.5 WETTING OR MOISTURE

Details of drainage construction in large sand filters are dealt with in Section 7.3, as is also the work of Yoder and Empson (1958a). The latter work concerns the ability of the lower layers of a sand filter to act as a water condenser while the dry upper layers of sand remain an effective aerosol filter. Difficulties leading to an increased pressure drop across a Savannah River sand filter as a result of ground water leakage are discussed in Section 8.1.2.

6.5.1 Steam-injection Tests

Steam injection into a contaminated gas stream was

postulated as a means of building up particle or droplet size and thereby increasing collection efficiency. However, injection of steam into a gas stream before it entered a scrubber had little effect (Work, 1948, p. 6). Tests with coarse 16-20 mesh Hanford sand at two to three times the steam needed for saturation gave varied results: two notable increases in filtration efficiency, three instances of slight decrease, and no appreciable effect in the rest. Under the test conditions, the magnitude of the effect of steam injection was comparable to that caused by normal variations of aerosol distribution (ibid., p. 11).

Lapple (1948a, pp. 21-22) proposed that the first large Hanford sand-filter bed be provided with a drainage capability of up to 10,000 gal/day since steam injection might eventually be used as a booster or standby alternative for a second fan, as a way of increasing particle collection efficiency in the sand bed, or as a possible method for scrubbing out iodine or other active gases.

If water were injected into the air stream entering the scrubber (for dissolver off-gases), drainage requirements for a sand filter to collect the water would be ~6000 gal/day. Venting the off-gases into the sand filter for entrainment removal might allow recirculation of the water and a reduction in drainage to <600 gal/day. Effluent water could be jetted over the sand bed for disposal or circulated over the packing to allow much of the water to evaporate. In all such cases, caustic or similar reagents must be added to fix the iodine and prevent its reevaporation from the sand bed (ibid.).

If no scrubber were used and iodine were not absorbed on the sand, the iodine might still be scrubbed out by steam injection at rates causing the steam to condense and the iodine to be absorbed in steam droplets removed in the sand filter. A small amount of reagent should be injected at the same time to fix the iodine. Otherwise, the steam-injection rate must be high enough to prevent evaporation in the sand filter; in this type of operation, steam might be injected into all ventilation gases to obtain the highest possible collection of all radioactive matter entering the sand filter (Lapple, 1948a, p. 22).

The dissolver off-gas problem was eventually solved by using separate fiberglass filters for aerosol removal and silver reactors (silver nitrate-coated Berl saddles) for iodine removal with a 99.9% collection efficiency (Basewitz, 1954a, pp. 72, 76; 1954b, pp. 40-47).

6.5.2 Moisture Capacity of a Sand Filter in a Protective Shelter System

The sand filter has a leveling effect on the humidity of the air in a shelter. Having a large heat capacity, it can cool flowing air below its dew point, and the condensed water is taken up by the sand (van Zelm and Clarenburg, 1966, pp. 16-18). A cubic meter of sand can absorb up to 4 kg of water. In one experiment, air at 40°C saturated with water vapor was passed through a laboratory sand column, initially at 20°C. For more than 120 hr, the excess water vapor was taken up from the air with no more than a 10% increase in resistance to air flow and temperature of outflowing air. Calculations based on this experiment indicate that a large heat loss to the environment must be assumed and that the water content of the sand should have risen to ~9%. Sand contains about 3.5% water when saturated, but water running out the column was not mentioned.

In another experiment, air was drawn continuously through a full-scale sand filter for 55 days. The outside air temperature varied from 12 to 30°C; the sand-filter temperatures varied from 13 to 17°C. No water dripped from the bottom of the filter, and no difference was found in the water content of sand samples taken at the top and bottom of the filter. Apparently, any condensed water reevaporated during the day-and-night cycle.

In a shelter system, air is normally drawn through the sand filter from top to bottom; however, reverse flow might be desirable under extreme conditions in which water condenses and must be drained off, preferably outside the shelter. If a downflow filter were used, any toxic substances in the condensate could recontaminate the air entering the shelter after flowing downward through the sand filter. The sand filter can take up considerable moisture and, if upstream from active charcoal, the latter would become saturated less rapidly and adsorb a greater quantity of other gases.

6.6 PROTECTION AGAINST NUCLEAR, CHEMICAL, AND BIOLOGICAL AEROSOLS

A test dust of clay particles, <5.0-53.5 μm, was drawn through a sand column 60 cm deep and 32 cm in diameter for 10 hr at a rate of 600 liters/(min)(m^2). Of a total of 43.9 g of clay dust, 80% was deposited in the first 1.5-cm sand layer. The collection efficiency was nearly 100%. In a second test for 8 hr at 1000 liters/(min)(m^2) with a total of 48 g of clay dust, 63% was deposited in the first 1.5 cm of sand. Although collection efficiency was nearly 100%, a marked increase in the resistance to airflow was noted (van Zelm and Clarenburg, 1966, pp. 25-27).

Another test gave 99.9% sand-filter collection efficiency in the retention of radioactive disintegration products of thorium B. Penetration of dioctylphthalate aerosol (0.3-μm particle size) was 1.5% in dry sand and ~10% in sand with 0.8% water content. Penetration of ammonium chloride aerosol (1.0-μm mean particle size) and methylene blue (0.4-μm mean particle size) was 2.5% in sand containing ~0.3% water at 80% relative humidity.

For aerosols of paraffin-oil and tricresylphosphate (<4 μm with a mean particle size of 0.3 μm), sand-filter efficiencies were 99.4-100.0%, increasing with increasing

percentages of sand grains smaller than 1 mm (ibid., pp. 28-29).

Tests with bacteria spores of bacillus subtilis (95% of particles <0.6 μm) were conducted using a 100-cm-high sand column. With air velocities of 600-1200 liters/(min)(m^2) and incident spore concentrations of 656-1703 particles/liter, the exit spore concentration varied from 3 to 48 particles/liters and the penetration ranged from 0.4 to 6.2%.

Conclusions from the various tests were that a sand filter could give essentially complete removal of particles >5 μm and could thus give satisfactory protection from usually large radioactive fallout particles. Large particles cause an increase in pressure drop as filtration proceeds. A sand filter only partially retains smaller particles, including bacteria. Penetration of smaller particles will be a few percent, varying with air velocity and water content of the sand. A sand filter does not give adequate protection from chemical and biological aerosols in a protective shelter (ibid., pp. 29-30).

6.7 THE SAND FILTER AS PART OF THE AIR PURIFICATION SYSTEM IN A SHELTER

According to van Zelm and Clarenburg (1966, pp. 32-34), an airflow rate of 0.5 m^3/(min)(m^2), which corresponds to a linear velocity of ~1 cm/sec, has been established for sand filters to be used as the main filters in West German shelters. Since the air supply per person is given as 30 liters/min, a shelter for 100 persons requires 3 m^3/min of air. The cross-sectional area of the filter is then 3/0.5 = 6 m^2. This is equivalent to ~10,000 kg of sand for a filter depth of 100 cm.

Long periods of confinement in a shelter (i.e., days) would require larger amounts of air and consequently larger cross-sectional areas for the sand filters. Economically, other types of air-cleaning systems may be preferable. Also, although the sand filter can protect the shelter against the effects of nuclear explosions occurring at a distance, it does not adequately protect against chemical and biological aerosols and is effective only for hydrolyzable war gases.

When a sand filter is used as a prefilter along with an aerosol filter and charcoal filter, it serves primarily to level out the effects of nuclear explosions and to control the shelter climate. A higher linear velocity 1 m^3/(min)(m^2), is allowed for a sand filter used as a prefilter in a West German shelter. However, larger amounts of air are needed for protection periods of long duration, and thus sand filters with larger cross-sectional areas are required.

Other tests (ibid., p. 15) had shown that overpressures which are behind or upstream from a sand filter and result from an incident shock wave are large enough to damage an aerosol filter (a particulate paper filter). An aerosol filter normally can withstand overpressures of no more than 0.5-m water gauge. An expansion volume and an antiblast device must be used in conjunction with aerosol and charcoal filters.

More recently, coarse-gravel (30-50-mm particles) filters have been substituted for sand in prefilters since gravel has the same properties for shock wave attenuation and heat absorption but much lower resistance to airflow. A greater airflow is possible with the same pressure drop as in a sand filter. Along with a coarse-gravel filter, an expansion volume and antiblast valve help to protect the aerosol filter and to keep the shock wave out of the shelter.

7. BED CONTAINMENT STRUCTURES

7.1 GENERAL COMMENTS

Solvay (1889) pioneered the idea of fixed-bed sand filters for freeing gases of "impalpable dust or of vapor in the vesicular state." A cylindrical vessel of metal or sandstone, either with or without a steam jacket, furnace, or other heating device, is provided with a cover having a gas inlet pipe; the outlet pipe and drain are at bottom of the vessel. However, the gas flow may advantageously be reversed to flow upward through a perforated diaphragm, through a layer of small pebbles, a bed of gravel of increasing fineness, and finally through the sand bed. This arrangement is shown in Fig. 7.1. Dust could be removed at the bottom in the upflow arrangement. With a downflow pattern, periodic raking of the upper part of the sand would be required to renew the surface. This could be done manually through a manhole or by installing an internal rake mounted on a central vertical shaft.

Krupchatnikov (1966) describes a similar low-output granular-bed filter in which gases flow downward through the filter medium, which is periodically loosened with a shaking mechanism or manual aluminum rake; a rubber sheet behind the rake teeth levels the surface. Figure 7.2 shows details of the filter (ibid., p. 99).

Both devices are in principle similar to the laboratory-scale sand filters used at Hanford before the installation of full-scale beds designed to remove radioactive aerosols from process gases prior to stack discharge. However, these Hanford beds did not include in their design upflow of any type of device for cleaning the "fixed" filter medium. The first laboratory-scale filter consisted of a 12-in.-diam vertical tank with a 1-in. gas-inlet pipe at the bottom and a 1-in. gas-outlet pipe at the top; pressure taps were located in the inlet and outlet pipes near their connection to the tank. A second laboratory-scale filter consisted of a 22-in.-diam vertical drum with 2-in. gas-inlet and -outlet pipes at bottom and top; a drain was located in the bottom of the drum, and pressure taps in the side of the drum were

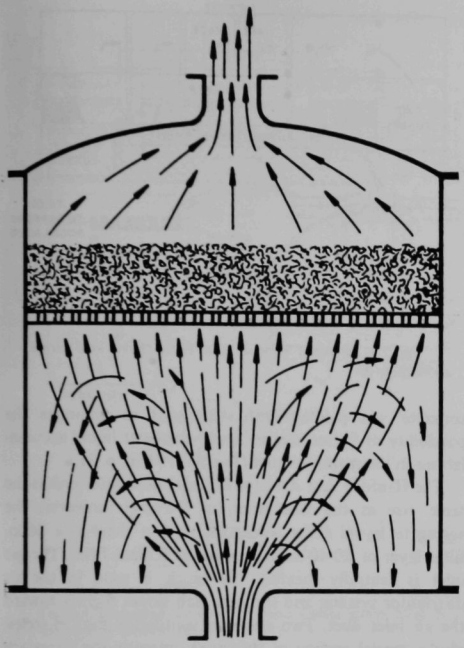


Fig. 7.1. Upflow Filter for Removing Dust in Gas Purification. Filter medium is either granular (sand) or fibrous (asbestos), supported on a perforated diaphragm. (Solvay, 1889; British Patent 18,573.)

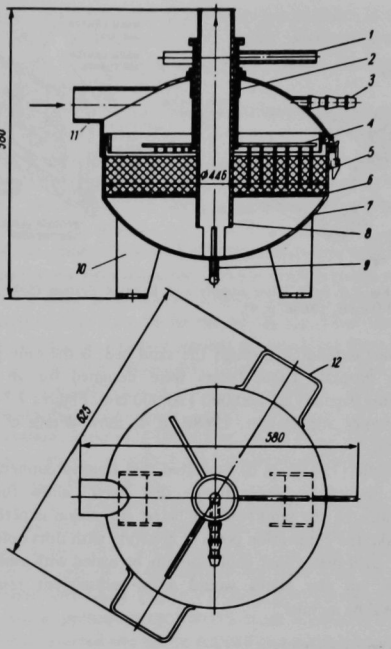


Fig. 7.2. Granular-bed Filter with 0.15-m^2 Filtering Surface Area (Krupchatnikov, 1966, p. 99). 1—Lever for rotating the loosening mechanism; 2—Sealing box; 3—Tube to feed in solutions; 4—Loosening mechanism; 5—Granular packing; 6—Grid; 7—Mantle, 8—Air-outlet tube; 9—Solution-drainage tube; 10—Support; 11—Air-inlet tube; 12—Handle.

located above and below the packing. An 8-mesh screen welded to the sides of the tank provided support for successively finer grades of sand. There was at least a 3- to 6-in.-high space above and below the packing (Lapple, 1948a, p. 6).

The Kellex sand filter (Kellex, 1949, p. 29) was ~2 in. in diameter with a drain at the bottom and a manometer across the bed to measure pressure drop. The first test sand filter of Blasewitz *et al.* (1951, Pt. 1, pp. 84-99) was a 4.5-in. steel unit with a 10-mesh screen support for graded sand layers. Airflow was upward, and pressure taps were located above and below the filter, in the plenum chamber, and at the interfaces of sand layers. The second and third test units were Lucite tubes; the third test unit is shown schematically in Fig. 5.2. Thomas and Yoder (1956a, Pt. 1, pp. 108,111) also used Lucite holders for sand tests. Glassmire (1956, Pt. 1, p. 52) used in 8-in.-square filters with ground tuff held between 12 and 20 U.S. mesh wire screen. Such small-scale columns served well in laboratory and pilot-plant studies, which led to more intricate designs of the large full-scale sand filters such as those at Hanford and Savannah River processing plants, discussed below in more detail.

7.2 SUPPORT

To minimize any hazard around the Hanford sand filter, the filter was located on the suction side of the fan and vented to the stack. The ground beneath the sand filter was nearly impervious to inleakage of air, and the walls and roof were made of concrete covered with an asphaltic membrane with an overlap at the concrete junction points to ensure air-tightness. The floor was also concrete for ease of placing the air distributor cement blocks and tile drain pipes. The dimensions of the East and West Area Hanford filters were set arbitrarily at 110 ft long, 48 ft wide (108 ft by 46 ft inside dimensions), and ~8-1/2 ft deep to give a filter cross-sectional area of ~5000 ft^2, required for the desired air-handling capacity of 30,000 ft^3/min at a superficial gas velocity of 6 ft/min (Lapple, 1948a, pp. 20, 16).

The two Savannah River Plant sand filters (Sykes and Harper, 1968a, p. 216) are patterned after those at Hanford. They are 100 ft wide, 240 ft long, and 8 ft deep; walls are waterproofed concrete. The roof, supported by

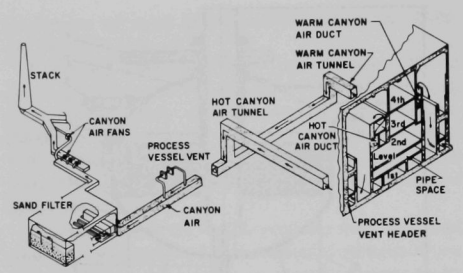


Fig. 7.3. Sand Filter Supply and Exhaust System (Sykes and Harper, 1968b, p. 4).

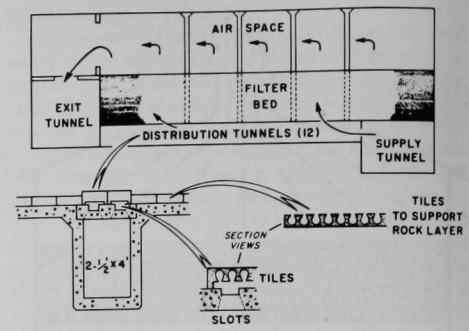


Fig. 7.4. Sectional View of Sand Filter (Sykes and Harper, 1968b. p. 4).

columns extending through the sand bed, is the only part above ground. These filters were designed for an air-handling capacity of 100,000-130,000 cfm. Figures 7.3 and 7.4 (Sykes and Harper, 1968b, p. 4) show details of the system.

Lapple (1948b, p. 6) suggested that flanged connection ports include a blank flange that would allow future additions to the sand filter. A better suggestion is perhaps to make the connection ports of concrete with slots holding loose steel plates that could initially be sealed with asphalt. Hooks on the plates would allow subsequent remote removal by a crane.

7.3 AIR CONDUITS

Good air distribution through a sand filter can be achieved through successive layers of closely graded gravel and sands which become progressively finer toward the top; such a bed serves as a support for the fine filtering layer. Details of the aggregate and sand beds are described in Section 2.2. To secure good air distribution across the fine sand layer, the pressure drop through the entering and exit sand layers and ductwork should be small compared to that through the fine sand layer (which should be of reasonably uniform thickness–Work, 1948, p. 15).

The Hanford 200 West Area sand filter has a 5-ft-high, 6-ft-wide inlet manifold running along the bottom of the 110-ft side of the filter. The air passes from the manifold through a series of concrete blocks (16 by 12 by 8 in., having 45% free port area) laid side by side over the bottom of the sand filter with the hollow ends pointing into the inlet manifold and separated by 1/2-in. spacers to allow gases to diffuse upward. The block faces that are perpendicular to the inlet manifold touch. The cement blocks are covered with 2-3-in. aggregate and with successively finer layers including a 24-in. layer of 20-40 mesh sand through which the gases are filtered before final entry into a plenum chamber. The gases then pass between the concrete roof beams to an outlet manifold at the top of the 48-ft side of the filter. The unit is operated under negative pressure using one ventilation fan (ibid., p. 16). The air inlet side of the concrete was painted with Americoat to minimize the possibility of failure due to heavy corrosive liquid accumulations in the manifold inlet (Lapple, 1948b, p. 3).

The Hanford East Area (or B Plant) sand filter unit is the same size as the West Area (or T Plant); however, the aggregate layers differ somewhat in that there is a 36-in. filter layer of 20-40 mesh sand in the B Plant filter. The gas inlet is centrally located; tile block is used in the air distributor system; and the base slab slopes slightly toward the air inlet duct. Two electrical ventilation fans in series, plus a special section of ductwork, provide the necessary suction (Stainken, 1949, pp. 32-33).

The Savannah River sand filters (Sykes and Harper, 1968b) consist of graded layers of sand and gravel. Air from 12 tunnels connecting to the main supply tunnel is distributed by special tiles (see Fig. 7.4) upward through 1-1/4–3-in.-diam rocks, through successively finer layers to the main filter layer of 30-50 mesh and (3 ft deep), and then through coarser sand and gravel, which prevent entrainment of the sand, finally passing through exit ports to an exhaust tunnel and out a 200-ft stack (see Fig. 7.3).

Lapple (1948a) recommended that provision should be made in the sand filter manifold for tieing in a second sand filter or other air-cleaning device in parallel to meet future demands and to allow cutting a failing unit out of service (Lapple, 1948a, p. 21).

It was suggested that pressure taps and sampling ports be built into a sand-filter unit; taps can be installed at various elevations by casting pipes into the concrete wall (Lapple, 1948b, p. 5).

Provision for a positive end fastening of the damper is suggested, and a butterfly type is preferred over a pendulum type. A butterfly type end fastening is more nearly balanced, making it possible to control airflow more easily.

Other suggestions include providing excess static pressure in fan specifications; fans can initially be run at lower speeds with smaller motors. Filter beds can be designed to operate at gas velocities of 10-20 ft/min by increasing the

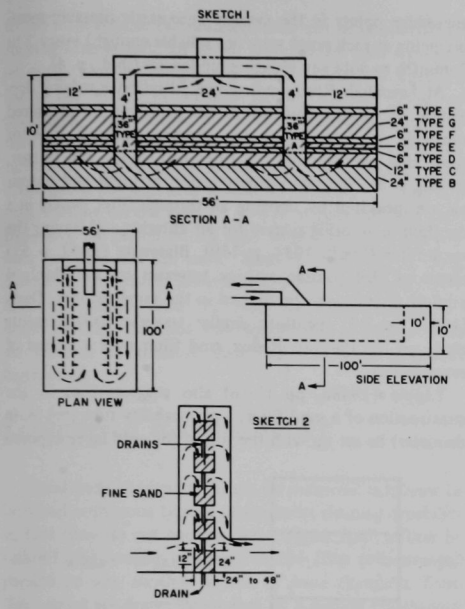


Fig. 7.5. Suggested Designs for Sand Filters Which Need No Air-distributor Blocks (Lapple, 1948b).

depth of fine sand; corresponding static pressure differentials will be ~20-50 in. of water (Lapple, 1948b, pp. 5-6).

An arrangement that eliminates the need of air distributor blocks is shown in Fig. 7.5. Dimensions are designed for operation at 30,000 cfm of air at 6-ft/min superficial gas velocity through the sand bed. The Sketch 2 design eliminates all supporting distributor blocks and aggregate, using only fine sand with 2-1/2- to 3-ft effective depth for collection efficiency. The design in Sketch 1 is probably preferable for large gas volumes; the Sketch 2 design would probably require metallic construction with multiple units in parallel for large gas volumes, but might be a better choice for small gas volumes (Lapple, 1948b, p. 6).

7.4 DRAINAGE

The West Area sand filter floor at Hanford was provided with sixty 6-in. tile pipes with an expected drainage capacity of 250 gal/day. This was considered adequate for handling any condensation occuring during normal operation; the gas inlet manifold should also have drainage holes along its length. A drain trench was also installed along the 110-ft side away from the inlet manifold together with main ports at the ends of the inlet manifold. These were blanked out, but could provide additional future drainage should steam injection be used or if the filter were used as a crib for water from the dissolver off-gas scrubber. If one of the latter modifications were made, potential drainage capacities of 6,000-10,000 gal/day might be required (Lapple, 1948a, pp. 20-21).

Other suggested methods for draining large volumes of water daily were (1) covering the aggregate layer with a thin concrete slab to support the concrete air distributor but leaving 6-in. drain ports, or (2) settling the concrete blocks into a precast concrete floor, subsequently placed on the aggregate (ibid., p. 21).

In the construction of the Hanford East Area sand filter, no provisions were made for drainage since drainage would have to take place against a fairly high air velocity. A suggestion that 2 by 4's be placed on the filter floor to provide drainage channels was not accepted, the floor being cast without this precaution. It was expected that only short periodic shutdowns would be required to permit any necessary drainage to occur (Lapple, 1948b, pp. 4-5).

Savannah River sand filters have sumps in the supply and exhaust tunnels to collect any condensed moisture (Sykes and Harper, 1968b, p. 2).

Yoder and Empson (1958a, pp. 85-86) found that very moist aerosols passing upward through a sand filter condense in the filter voids and soon clog the filter. The pressure builds up at the inlet as the sand filter becomes saturated with water. Figure 7.6 (ibid., p. 89) shows a sharp decrease in pressure drop after 19 hr, at which point water begins to channel and can be drained to a sump beneath the system. Thus, the filter can be designed so that the lower few inches of sand serve as a water condenser, while the remaining sand is dry and serves efficiently as an aerosol sand filter.

Figure 7.7 shows a compound sand filter (Yoder and Empson, 1958a, p. 86) designed to decontaminate the off-gases from radioactive wastes fixed in a sintered clinker. Dry sand effectively filtered particulates, and the collection efficiency increased exponentially with depth of bed. For very moist aerosols, water condensed in the filter voids in the lower few inches of sand and could be drained off to a sump below. Ruthenium-106 was effectively removed in the condensate. A bed of soda lime removed oxides of nitrogen and iodine was trapped at the sand-soda lime interface. Activated carbon removed any traces of iodine and reduced traces of nitrogen oxides to <1 ppm nitrites. At 0.1-cm/sec air velocity, 99.995% of all particulates and fission gases were removed, except xenon and krypton.

7.5 MONITORING

When the Hanford full-scale sand filters started operation in October 1948, daily measurements were made to determine the performance of the sand filter and the quality of the stack effluent. Collection efficiency was determined by taking samples of the main ventilation gases both upstream and downstream from the sand filter and

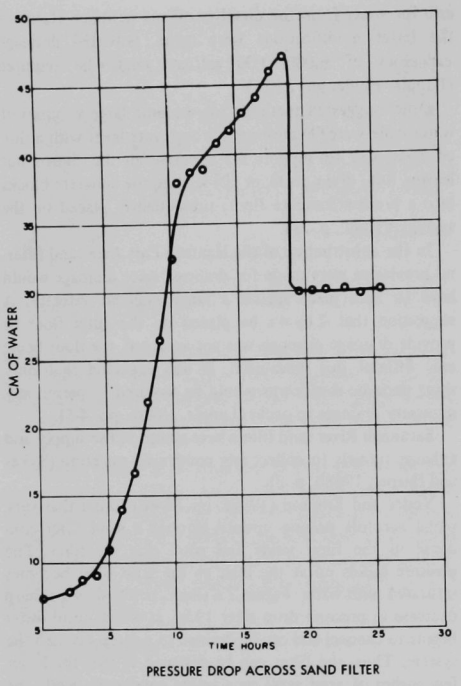


Fig. 7.6. Buildup of Pressure in Sand Filter from Saturation with Water (Yoder and Empson, 1958a, p. 89).

passing the samples through CWS Type 6 filter papers, which were subsequently monitored and analyzed for activity by various means (Lapple, 1949b, pp. 1-2).

Pressure differentials were measured. On the basis of fan-performance curves, making due allowance for fan speed, these measurements indicated airflows through the sand-filter systems of 32,000 (East Area) and 27,000 cu ft/min (West Area). More reliable information could have been obtained on the airflow through the sand filters by pitot traverse, but the internal-ribbed ductwork was not especially suitable for such measurements and the pitot differential would have been only ~0.03-0.06 in. water. Another method suggested involved introducing a contaminant foreign to the system–radioactive tracer, ammonia, or sulfur dioxide–at a known rate into the ductwork downstream from the sand filter; the concentration of contaminant (measured after the ventilation gas leaves the first or second fan) serves as a direct measure of airflow in the system, based on the degree of dilution and the rate of introduction (ibid., pp. 2-4).

A series of incremental pressure-drop measurements was recommended (by direct differential readings between successive points in the system since static pressure measurements at each point were not reliable enough) every 2 to 3 months to note any plugging tendencies (ibid., p. 4).

At Savannah River, radioactive filtration involving deposition of gamma emitters in the sand can be measured routinely by lowering an ion chamber through monitor tubes that pass through the filter bed (Sykes and Harper, 1968b, p. 3). The radioactivity levels for input and output air are measured by drawing air through filter papers in a constant-monitoring system for air entering and leaving the sand filter (Clark, 1954, p. 159). Blasewitz (1949, p. 51) mentions that routine activity traverses on the Hanford sand-filter bed were performed in the same manner. Davis (1958, pp. 2-3) mentions similar traverse measurements made on the Hanford Redox sand filter over a period of several years.

Lapple (1948b, pp. 15-16) also suggests that in the construction of a sand filter, a permeability tube (~4 in. in diameter) be set up with the top of the sand layer exposed

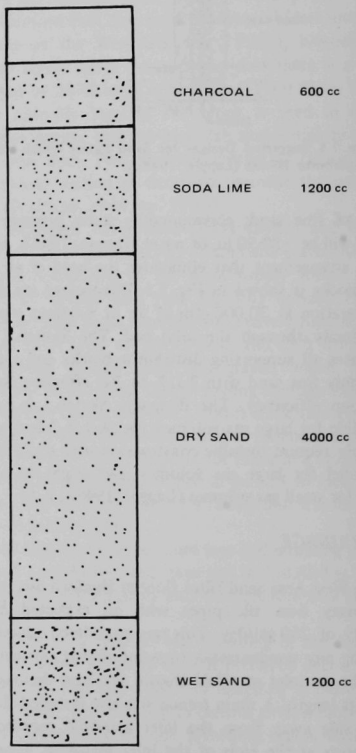


Fig. 7.7. Compound Sand Filter. Column diameter, 9 cm; flow rate, 500 cc/min (Yoder and Empson, 1958a).

to the atmosphere. Permeability tests can be conducted by sucking atmospheric air down through the tube by steam jet or by blowing compressed air up through the sand. To study the effect of surface loading on the degree of packing, a weight-loaded piston of diameter slightly smaller than the permeability-tube ID can be placed on the sand surface to secure initial compacting. The loading range investigated per unit area should be equivalent to that of a man walking on the sand on foot or supported on boards. Dropping the piston on the sand would be equivalent to a man jumping on the sand. When permeability is being measured, the piston is removed. In laboratory-scale tests, sand was poured into the tube for loose packing; for dense packing, the tube was rapped with a hammer until no increase in pressure drop occurred with additional hammering.

7.6 INDUSTRIAL FIXED-BED FILTERS

Fixed beds of granular filters for industrial uses must be provided with some type of intermittent cleaning capability so that they do not become dust-clogged. Such a filter by Lühr (1966) consists of several narrow filter cells arranged parallel to one another in one or more chambers. Dust-laden gases are drawn downward by a suction fan through layers of sand or kisselguhr in the filter cells and pass out through slits in the bottom as cleaned gases.

Periodically, each filter cell is isolated from the dust-laden gases. Filter material is cleaned by passing a cleaning gas countercurrently to the usual direction, using a vent nozzle moved back and forth over cell apertures at the bottom. The granular filter material is agitated by the upflow of cleaning gas and dust, which pass out through a system of flaps at the top of the cells. No sand is lost in the cleaning operation, since the sand is supported between horizontal walls of metal mesh or screening in closed cells.

An additional patent by Lühr (1967) consists of "a plurality of filter cells arranged in a plurality of vertically spaced, horizontally extending rows in each of one or more filter chambers." Filter cells contain sand or kisselguhr. This vertical arrangement allows for much greater filter area and thus an increase in the rate of gas filtration without a proportional increase in the height of the installation. Squires (1967) developed a means whereby gases are treated by contact with granular solids in coal gasifications, catalytic contacting, gas absorption, gas adsorption, and filtration of particulate matter from gases. Gas passes through perforated walls and is filtered by a vertical column of sand supported by horizontal louvers. When sand is to be regenerated or cleaned, the gas inlet is closed and a short blast of gas is blown through the bed from the outlet side. Spent sand spills over the edge of the louvers and drops to the bottom for removal. Fresh sand is added at the top of the column.

7.7 MOVING-BED SAND OR GRANULAR FILTERS

Moving-bed filters employed in the removal of high concentrations of aerosols or dust from gases at ordinary temperatures are described here. Others designed for high-temperature applications are described in Sections 6.3.3 and 6.3.4.

Fiechter (1919) patented a device in which a gaseous medium to be cleaned is introduced at the top of a movable plan sieve—a rotating disc of perforated metal or mesh—covered with a layer of sand or other granular filter material. The gas is purified as it is passed downward through the sand layer and is drawn off at the bottom by a suction fan. Removal and purification of filter media may be effected continuously or intermittently by a revolving worm conveyor mounted over the plan sieve, and a vertically adjustable scraper bar spreads the cleaned filter medium to the desired layer thickness. The method of cleaning the spent sand or filter medium is not specified.

Another patent by Fiechter (1922) involved the use of a movable sieve on an endless belt, carrying a horizontal layer of sand, through which a gaseous medium can be filtered downward under suction or pressure. A pair of inner guide walls prevent sand slipping off the belt, which is slightly lower at one end, allowing spent sand to trickle into a cleaning device and be returned (via an elevator) to the hopper above the opposite or higher end of the belt.

Fournier (1936) designed an apparatus for filtering gases by means of a filtering material such as sand falling over (1) horizontal slats that may be vibrated or (2) a combined system of slats and sieves. The gas passes transversely through the layer of filtering material and between the slats of each series. Hammer vibrators are suggested as a means of increasing the filter surface by facilitating the flow of filter material and partially cleaning it. An endless chain of buckets or rakes continuously feeds clean sand into the upper hoppers and transports soiled sand to a cleaning device. In the cleaning device, the sand flows by gravity down a sinuous channel against an upflow of cleaning gas that removes the dust to a cyclone dust separator.

Berry and Fournier (1939) presented a more limited version of the above as a German patent. Dust, soot, etc., are removed from gases and vapors by passing the gas transversely through a granular filter of material falling in piles with natural angles of repose over a series of horizontal slats. The angle of the slats may be varied, and filter material may be removed at the bottom of the apparatus for cleaning and replaced at the top.

Carney (1944) devised an apparatus for separating carbon-black dust entrained in a stream of gas or air by passing the gas upward through a bed of carbon-black granules contained in a rotating cylinder. A spiral conduit, connected at the bottom of the cylinder and wrapped around it, rotates with the cylinder and lifts the granules to the top of the cylinder while the carbon dust is agglom-

erated to the granules. The cylinder is ~6 ft in diameter and mounted at an angle equivalent to the angle of repose of the carbon agglomerates, so that there is continuous overflow into a downpipe of agglomerated carbon granules to be commercially finished and classified. Seed granules of carbon are added at the top of the cylinder in sufficient quantity to produce a range of commercial sizes upon agglomeration.

Wainwright *et al.* (1956) consider the moving-bed filter described by Egleson *et al.* (1954), with emphasis on its ability to be used at high temperatures with gases containing considerable water. An example is its use in the purification of synthesis gas produced by reacting pulverized coal with steam and oxygen. An ideal synthesis gas for making liquid fuels would consist of a mixture of pure hydrogen and carbon monoxide in the proper proportions. However, undesirable impurities obtained in gasification processes include dust, carbon dioxide, oxygen, organic sulfur compounds, and hydrogen sulfide. Dust is removed from synthesis gas because of its undesirable effects on the synthesis catalyst, compressors, and fixed beds in the system. Satisfactory purification can be achieved by passing the gas upward through a bed of coke that is continuously moving downward. Coke can be removed at the bottom, dust washed away, and the coke returned to the top of the filter. The desired purity can be obtained by varying the fineness of coke. Tests at Oppau, Germany, on acetylene split gas reduced the dust content from 5 to 0.03 grain/100 ft^3 (a 99.4% removal) with 12 in. of water-pressure drop. Tests at Morgantown, West Virginia, with 1.25 to 2.5 in. water pressure, resulted in removals of 85-98% of the dust and outlet dust concentrations of 0.2 to 3 grains/100 ft^3. Dry coke beds generally gave better dust removal than wet beds. Thus, at a pressure drop of 4 in. water across the bed and a bed height of 0.83 ft coke, a dry bed gave ~99.98% dust removal with 134 grains/100 ft^3 inlet dust concentration, while a wet bed gave ~99.8% dust removal with 97 grains/100 ft^3 inlet dust concentration.

8. APPLICATIONS TO ATOMIC-ENERGY INSTALLATIONS

Although the original sand filters in atomic-energy installations were employed to remove radioactive particulates from off-gases in atomic fuel reprocessing plants, sand filters have since been incorporated in the ventilation systems of some reactors.

8.1 FUEL-REPROCESSING PLANTS

The details of physical construction of the Hanford Atomic Products Operation and Savannah River Plant sand filters were dealt with at some length in Section 7. Section 8.1 will attempt to evaluate their actual performance, costs, and life expectancy.

8.1.1 Hanford Atomic Products Operation

The Canyon Buildings at Hanford, where irradiated uranium is processed to separate plutonium from uranium and fission products, each contain 40 cells in a line. The flow of ventilation air through this complex prior to October 1948 is shown in Fig. 8.1 (Work, 1948, Fig. 1).

Activity discharged from the 200-ft stack was thought to be adequately dispersed by dilution until late in 1947, when "hot specks" appeared on the ground around the stack area. Samples of ventilation air were filtered through CWS Type 6 paper at points upstream of the fans, downstream from the fans at the stack base, 50 ft up the stack,

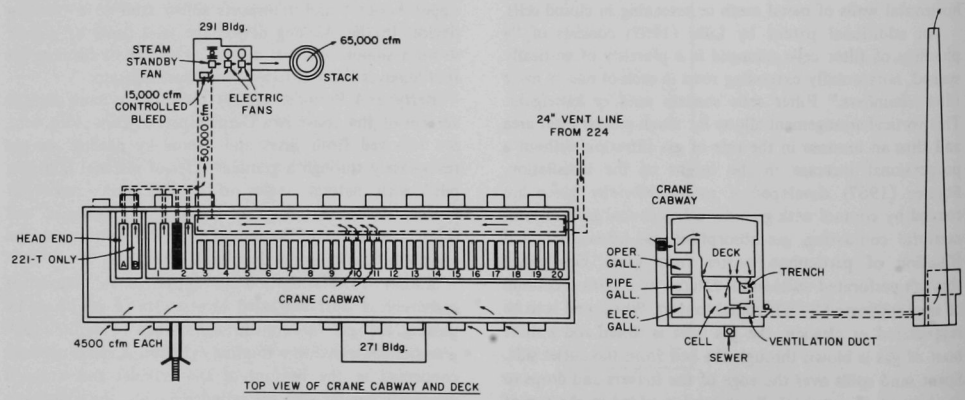


Fig. 8.1. Ventilation Diagram of Processing Area, Canyon (221) Building (before Oct 1948) (Work, 1948).

and at the dissolver off-gas lines entering the stack breeching. Sample analyses showed that particles ranged up to 0.1 and even 1.0 mCi; samples taken upstream of the fans consisted of fine dust or spray, but no large particles; samples taken downstream from the fans and 50 ft up the stack contained many particles that were magnetic and high in iron concentration, resembling rust from ventilation ductwork. The deteriorated black iron ductwork was replaced with stainless steel. This eliminated the large particles, but not the small active particles of spray or dust from the processing solutions. Interim efforts included installation of CWS Type 6 paper filters on each cell to filter all plant-ventilation air, and tests with a scrubber, an electrostatic precipitator, and a cyclone separator to reduce aerosol activity in the stack effluent (ibid., p. 4). However, when initial tests indicated that a 2-ft bed of 20-40 mesh sand gave >99% collection efficiencies at superficial gas velocities up to 10 ft/min, an intensive effort was made to determine the characteristics of sand filters with laboratory-scale columns. Typical data are summarized in Table 8.1 (Lapple, 1948a).

The full-scale sand beds were designed to handle 30,000 cfm of air with a superficial gas velocity of 6 ft/min. The arbitrarily set dimensions of 110 by 48 ft approximated the required cross-sectional area of 5000 sq ft. Operation of the T Plant (West Area) sand filter started October 15, 1948. After the system became balanced, the total airflow was ~25,000 cfm with a pressure drop of 4.0 ± 0.1 in water, a linear flow velocity of ~2 ft/min, and an average collection efficiency of 99.5%, based on instrument surveys and laboratory analyses of sample filter papers. Initial data for the first three weeks are given in Table 8.2 (Work, 1948, pp. 20-21).

The B Plant (East Area) sand filter started up on October 30, 1948, with two electric fans in series connected through suitable ductwork. With a 3-ft bed of fine sand, the pressure drop for this filter ranged from 5.8 to 7.0 in. of water with an airflow of 22,000-26,000 cfm and an average collection efficiency of 99.7-99.8%, based on initial data taken before the system was balanced (Work, 1948, pp. 21-22).

Early data indicated that the stack gases were recontaminated and that the overall decontamination factor of the stack effluent was only about 10. The problem seemed to be that dissolver off-gases were not passed through the sand filter, but were mixed with sand-filter effluent gases at the base of the stack. This problem is discussed at length by Lapple (1949a).

The main ventilation gases were monitored upstream and downstream from the sand filter daily to determine collection efficiency. Samples were passed through CWS Type 6 filter papers, which were monitored with a Cutie Pie radiation detector and also analyzed for α and β activity in the laboratory. A weighted average was derived for each filter paper, questionable values being omitted (Lapple, 1949b, p. 1).

TABLE 8.1. Sand-filter Performance (Lapple, 1948a)

Sand Filter							Collection Efficiency, %			
	Sand Bed						Cutie Pie		Laboratory	
Diam, in.	Type (Top to Bottom)	Depth, in.	Superficial Gas Velocity, V, ft/min	Steam Injection, lb/hr	Pressure Drop, Δp, in. water	Δp/V	$\beta + \gamma$	γ	β	α
12	Hanford 4–8 mesh	1	1.3	0	0.8	0.6	>99.6	>96	99.970	99.83
	Hanford 20–40 mesh	22	1.3	0	0.8	0.6	>99.3	>92	99.971	99.935
	Hanford 16–20 mesh	1	1.3	0	0.8	0.6	>99.7	>97	99.961	99.84
	Hanford 8–16 mesh	1	3.8	0	2.6	0.68	>99.8	>98	99.914	99.944
	Hanford 4–8 mesh	1	3.8	0	2.8	0.74	>99.8	>97	99.938	99.961
			9.3	0	5.4	0.58	>99.93	>97	99.950	99.68
			9.8	0	5.6	0.57	>99.96	>97	99.936	99.962
22	Hanford 20–40 mesh	20-1/2	2.0	0	1.0	0.5	>99.75	>97	99.994	99.991
	Hanford 16–20 mesh	1	4.9	0	2.6	0.53	>99.9	>99	99.97	
	Hanford 8–16 mesh	1	10.0	0	4.7	0.47	>99.57	>95	99.85	99.90
	Hanford 4–8 mesh	1	10.0	0	5.6	0.56	>99.75	>97	99.76	
22	Ottawa 20–30 mesh	20-1/2	1.0	0	0.2	0.2	>98.8	>90	99.988	99.5
	Ottawa 1/4–1/2 in.	2	2.0	0	0.5	0.25	>99.0	>90	99.23	99.37
			2.0	0	0.5	0.25	99.44	98.3	99.72	99.34
			4.9	0	1.4	0.29	94.0	>92	95.2	93.2
			10.0	0	3.3	0.33	90.0	89.5	90.6	92.9
			10.7	0	3.5	0.33	91.0	>86	84.8	89.8
22	Hanford 16–20 mesh	21-1/2	2.0	0	0.3	0.15	97.85	98.0	98.20	
	Hanford 8–16 mesh	1	2.0	0	0.35	0.18	98.27	98.7		
	Hanford 4–8 mesh	1								
			3.8	0	0.6	0.16	95.0	97.0		
			3.8	0	0.75	0.20	95.0	95.0		
			3.8	1.5	0.7	0.18	>98.2	>83		
			7.6	0	1.0	0.13	90.0	93.3		
			10.0	0	1.5	0.15	86.3	84.0		
			10.0	7.0	1.4	0.14	90.0	90.7		
			10.0	7.0	1.4	0.14	83.3	93.0		

TABLE 8.2. Initial Performance Data on Large Hanford Sand Filters

Sample No.	Activity of Monitoring Filters, mCi of beta activity: Upstream from Filter[a]	Downstream from Filter[a]	Fifty feet up Stack	Efficiency,%: Based on Lab Analysis	Based on Instrument Surveys
			T Plant Unit		
1[b]	9.64	0.65	4.77	93.6[c]	>97.1
2	132	4.2	7.58	96.8[c]	99.8
3	154	1.8	7.26	98.8[c]	99.7
4	85.1	0.75	3.51	99.1	99.5
5	133	0.415	3.37	99.7	99.4
6	71.3	0.454	3.41	99.4	99.6
7	105	0.841	10.1	99.1	99.3
8	264	0.701	1.35	99.7	99.6
9	182	1.36	3.14	99.2	99.7
10	392	1.01	7.97	99.7	99.7
11	114	0.481	4.13	99.6	99.7
12	157	0.428	14.5	99.8	99.8
13	-	0.62	28.4	-	99.2
14	140	0.88	4.75	99.9	99.3
15	311	0.591	15.3	99.5	99.6
16	347	1.05		99.5	99.7
17	139	0.44	6.56	99.7	99.6
18	117	0.45	8.68	99.6	99.9
19	155	0.67	8.95	99.6	99.6
20	215	1.24		99.6	99.7
Ave[c]	153[d]		7.21[d]	99.54[c]	99.55
			B Plant Unit		
1	67.2	0.235	80.8	99.7	>99.8
2	44.2	0.060	-	99.9	>99.8
3	271	0.307	91.1	99.9	99.9
4	190	0.316	41.1	99.8	99.9
5	519	1.60	128	99.7	99.7
6	54.6	0.424	91.2	99.3	>99.9
7	439	1.12		99.8	99.7
Ave	220[e]	0.58[e]	86[e]	99.7	99.8

[a] Flow through the filters (approximately 1 cfm) is not recorded here, but was used in calculating efficiencies.
[b] First sample covered 8 hr, and others covered 24 hr.
[c] First three samples were not included in average, because of incomplete dissolutions of activity during analysis.
[d] Samples 1, 13, 16, and 20 not counted in averages.
[e] Samples 2 and 7 not counted in average.

Lapple believed that measured airflow (based on fan-performance curves vs pressure-differential measurements) of 32,000 and 27,000 cfm for the East and West Areas, respectively, were 5000 cfm higher than the actual airflows; however, based on previous experience with fan-performance curves, a 10% divergence is not unreasonable. Table 8.3 (Lapple, 1949b) summarizes the pressure measurements for the sand filters.

It appeared that no more than a 20% increase in pressure drop was due to bed compression. There was more compression in the East Area bed than the West Area bed.

Blasewitz (1949, p. 51) reports the first year's operation for both sand filters as "highly satisfactory," with no decrease in ventilation airflow or increase in pressure drop and with unchanged collection efficiencies of 99.4 and 99.8%, respectively, for the West Area and East Area filters. Routine traverse measurements with an ionization chamber indicated that appreciable activity had been deposited in the coarser sand strata below the Type G (20-40 mesh) layer and little activity had penetrated beyond 1 ft into the Type G layer. Meanwhile, a fiberglass filter was being designed to remove the particulate contamination from the dissolver vent gases, which have an average flow of 100 cfm. Curves of filtering efficiency vs bed depth and pressure drop vs bed depth for fiberglass and sand are presented in Figs. 8.2 and 8.3, respectively (ibid., pp. 55-56, Figs. 1 and 2).

Zahn (1953) notes that at the Redox Plant at Hanford, separate vessel vent systems of high-efficiency fiberglass filters and a sand filter were installed on the main ventilation air stream. The fiberglass filters were upstream from the sand filter. The Redox Plant ventilation system had less than one-tenth the radioactivity prior to its passage through the sand filter as compared to the activity in the ventilation air streams leaving the B and T Plant (Bismuth Phosphate Plants) sand filters. However, activity upstream from the Redox filter increased sharply in 1953, showing a need for a further investigation of sand filters and fiberglass for the Purex Plant design. Results tended to favor fiberglass.

TABLE 8.3. Pressure Measurements on East and West Area Sand Filters
(Lapple, 1949b, 1/13/49–1/17/49)

	East Area (B)	West Area (T)
Pressure differential, in. water		
Atmosphere to sand-filter inlet	2.15	1.15–1.20
Sand-filter entrance to bottom of G layer	0.45–0.50	0.60
Bottom G layer to plenum chamber	6.7–6.8	3.30–3.35
Plenum chamber to sand-filter outlet	0.1	0.1
Sand-filter outlet to upstream fan inlet	0.65	0.40
Across upstream fan (No. 2 fan)[a]	4.75	6.08–6.18
Between fans[a]	0.25–0.30[b]	
Across downstream fan (No. 1 fan)	5.15	
Sand-filter inlet to sand-filter outlet		
Measured	7.3–7.4	4.15–4.2
Calculated from other measurements	7.25–7.40	4.00–4.05
Atmosphere to downstream of upstream fan		
Measured	5.30	-
Calculated from other measurements	5.35–5.45	0.38
Atmosphere to upstream of downstream fan		
Measured	5.15[b]	
Calculated from other measurements	5.10–5.15[b]	
Atmosphere to downstream fan discharge (calc.)	0.0[b]	
Fan speed, rpm		
Upstream fan (nearest sand filter) (No. 2)	889	945
Downstream fan (nearest stack) (No. 1)	Not Measured	
Temp, °C		
Sand-filter inlet (therm. strapped to duct)	11	-
Sand-filter outlet (thermocouple)	-	14
Airflow, cfm (estimated from fan performance)	32,000[c]	27,000[c]

[a] Taps across a fan are located very near the entrance and exit of the fan. The fan inlet has a 45-3/8-in. ID (circular), and the exit is 34-3/8 by 47-3/4-in. ID (rectangular).

[b] Reading between the upstream and downstream fan is in the reverse direction of what it should be, being higher on the downstream side of the upstream fan. This may be accounted for by the fact that the upstream tap on No. 1 fan is on the outside of the 90° bend connecting No. 1 and 2 fans.

[c] On the basis of pressure differentials measured in the system, it is estimated that the actual airflow is 4000 to 5000 cfm less than these values. This would be compatible with the fan-performance curves if the latter were in error to the extent of being 10% high.

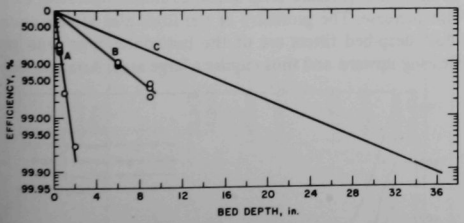


Fig. 8.2. Filtering Efficiency vs Bed Depth. Curve A, AA Fiberglas at 0.6 lb/ft^3 and 10 ft/min. Curve B, No. 55 Fiberglas at 6.0 lb/ft^3 and 10 ft/min. Curve C, Ottawa Sand, 30-40 mesh. (Blasewitz, 1949).

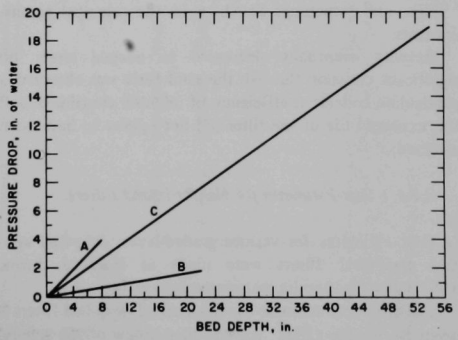


Fig. 8.3. Pressure Drop vs Bed Depth. Curve A, AA Fiberglas at 0.6 lb/ft^3 and 10 ft/min. Curve B, No. 55 Fiberglas at 6.0 lb/ft^3 and 10 ft/min. Curve C, Ottawa sand, 30-40 mesh. (Blasewitz, 1949).

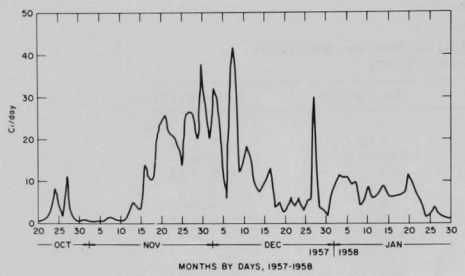


Fig. 8.4. Activity in Redox Sand Filter (Davis, 1958).

Davis (1958) discusses an increase of activity in the Redox sand filter. This occurred in November 1957, when values rose from ~1 Ci/day to a maximum of 44 Ci/day, as shown in Fig. 8.4 (ibid., Fig. 1). Failure of an H-4 oxidizer vessel and its subsequent removal from the H-cell caused the increase in activity. After the H-cell was flushed several times with the water-spray system over a 2-week period, the activity entering the sand filter was considerably lower. Although 44 Ci/day represented the largest amount of activity entering the filter in two years, it was not as high as the maximum reached in July 1954. Traverse measurements in the northwest quadrant are given for late 1957 and early 1958, Fig. 8.5 (ibid., Fig. 4), and also for the past four years. Measurements at the interface of the E and F strata of the filter medium (42 in. from the bottom of the filter) were believed to indicate most reliably the total activity in the filter. Gamma scans of inlet samples showed ^{103}Ru, ^{106}Ru, and sometimes Zr-Nb to be the principal gamma emitters.

Activity eventually decreased to normal levels; no significant emission through the sand filter was observed; a particulate collection efficiency of >99.9% continued; and the expected life of the filter did not appear to have been affected.

8.1.1.1 Cost Estimates for Hanford Sand Filters

Cost estimates for various graded-layer, deep-bed sand and glass-fiber filters were made at Hanford during 1951-1954. The results are summarized in Table 8.4.

The first cost estimate for fine-packed deep-bed filters is given by Lapple (1951, p. 145) in a review of the general types and characteristics of dust and mist collectors. Such beds, costing $2 to $5/cfm, can handle particles <1 μm, operate with 1-10 in. water-pressure drop, and consume 0.2-2.0 kW/1000 cfm. This type of filter is used to remove radioactive aerosols and sulfuric acid mists; granular filter medium is <4 mesh, and fibrous filter medium is <0.005 in. Packed beds are not available as commercial units, but are designed to meet specific requirements.

Lapple (1954, pp. 103-110) states that in the design of deep-bed filters, factors to be considered include collection efficiency or penetration, pressure drop, filter size, filter life, and available packing medium. The maximum tolerable activity level in the filter exhaust gases should be the primary design specification; however, since often neither the quantity nor the particle size of the aerosol activity is known, the practice is to provide as high a degree of decontamination as is reasonable possible. The pressure drop must not exceed 30-50 in. of water (which ordinary commercial fans can handle) so that multistage fans are not needed. Economics is an important factor, and the effect of the following items on total annual operating cost must be considered:

1. Power cost; directly related to pressure drop.
2. Fixed charges (maintenance and earning power of funds invested); directly related to the investment cost.
3. Depreciation; related to investment cost and to life of the filter.

A filter should be designed to operate at optimum velocity for minimum total annual cost. However, since the life of filters is not known, optimum gas velocities have been estimated—5-10 ft/min for sand filters and 15-30 ft/min for fibrous filters, with pressure drops in the range of 4-8 in. of water. Optimum gas velocity is dependent on aerosol size and concentration; for a finer aerosol and a higher aerosol concentration, a lower gas velocity would be optimum. Operation at higher gas velocities and pressure drops than those estimated would probably be more economical, but more knowledge of filter life is needed to determine this.

Other design features can also influence cost. One such factor is thickness of the sand layer. Along with the higher degree of decontamination obtained with additional layers of fine sand, pressure drop and thus annual operating costs also increase. The geometry of the filter also affects costs. Most deep-bed filters are of the horizontal type with gas flowing upward and thus require a large area. Arrangements

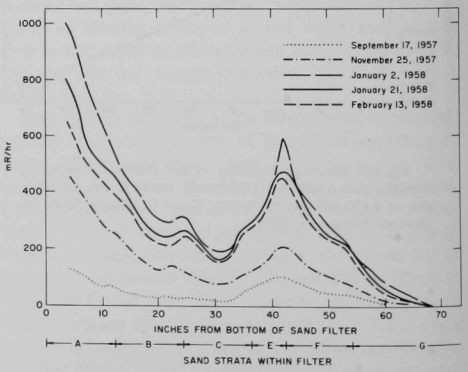


Fig 8.5. Redox Sand-filter (Northwest Quadrant) Traverse (Davis, 1958).

TABLE 8.4. Summary of Cost Estimates for Deep-bed Filters for Radioactive Aerosols at Hanford, 1951–1954

Type of Deep-bed Filter	Type of Filter Medium	Air-handling Capacity, cfm	Filter Size, w x l x h, ft	Plot Area, sq ft	Filter Medium Superficial Gas Velocity, ft/min	Press. Drop, Water Gauge, in. water	Activity Coll. Effic, %	Life Expectancy,[a] yr
Fine packed bed[b]	Granular (<4 mesh) or fibrous (<0.005 in.)	-	-	-	-	1-10	-	-
Typical Deep Bed at Hanford[c]	Sand	35,000	85 x 85 x 14	7,030	6	8	99.7	>5
	Fiberglas	35,000	28 x 70 x 9	1,960	25	5	99.99	>10
Deep-bed Filter Proposed for Purex Plant at Hanford[d]	Sand	126,000	-	30,800	5	7	99.5	>5
	Fibrous glass	126,000	-	4,300	50 & 20[e]	4	99.9	>5
Deep-bed Filters Proposed for Separations Plant at Hanford[f]	Sand	100,000	-	-	-	-	-	-
	Fibrous glass	100,000	-	-	-	-	99.99	-
	Fibrous glass	100,000	-	-	-	-	99.	-
	Standby[g]	100,000	-	-	-	-	99.	-

Filter Installation Costs

Type of Deep-bed Filter	Type of Filter Medium	Housing	Earthwork	Concrete	Roofing	Amer-coating	Filter Media	Sumps, Jets, Instr.	Lump-sum Contractors Overhead & Profit	Est. Lump Bid Price	Design Adminis. Costs	Contin-gency 10%	Total Project Cost Dollars,	Total Project Cost Dollars, cfm
Fine packed bed[b]	Granular (<4 mesh) or fibrous (<0.005 in.)	-	-	-	-	-	-	-	-	-	-	-	-	$2-5
Typical Deep Bed at Hanford[c]	Sand	$135,000	-	-	-	-	$ 60,000	-	-	-	-	-	$195,000	$5.57
	Fiberglas	$ 42,900	-	-	-	-	$ 67,200[h]	-	-	-	-	-	$110,000	$2.86
Deep-bed Filter Proposed for Purex Plant at Hanford[d]	Sand	-	$20,000	$360,000	$9,000	$10,000	$200,000	$6,000	$145,000	$750,000	$75,000	$75,000	$900,000	$7.14
	Fibrous glass	-	$ 5,000	$ 50,000	$3,000	$ 2,000	$188,000[h]	$5,000	$ 65,000	$318,000	$32,000	$32,000	$382,000	$3.03
													-	-
Deep-bed Filters Proposed for Separations Plant at Hanford[f]	Sand	-	-	-	-	-	-	-	-	-	-	-	$750,000	$7.50
	Fibrous glass	-	-	-	-	-	-	-	-	-	-	-	$375,000	$3.75
	Fibrous glass	-	-	-	-	-	-	-	-	-	-	-	$250,000	$2.50
	Standby[g]	-	-	-	-	-	-	-	-	-	-	-	$100,000	$1.00

[a] Fibrous glass filters assumed to have a life expectancy equal to or double that of sand filters.
[b] Costs for mild-steel construction; prices: 1945–1946 period (Lapple, 1951, p. 145).
[c] Filter data compiled in 1952 (Lapple, 1954, pp. 115–116).
[d] Zahn, 1953, Tables I and Appendix B.
[e] 50 ft/min in forefilter and 20 ft/min in cleanup filter.
[f] Blasewitz, 1954, p. 47.
[g] Standby filter for occasional use in emergencies or periods of unusually high activity.
[h] Includes supports for graded layers of fiberglass.

designed to conserve floor space usually add to the initial cost. Also influencing cost for granular materials such as sand is that the sizes available in quantity in a particular geographic region are limited.

The maximum life of a filter is controlled by the porosity of the most porous packing; however, since the porosity of sand can be varied over a very small range only, the porosity of a sand filter is essentially fixed. The graded layers of sand vary in nominal size by about a factor of two. Also important is the direction of gas flow. Upflow allows any condensate or entrained liquid to be removed by coarse packing at the inlet; in contrast, downflow allows any liquid condensate to reach the fine packing and markedly increase the airflow resistance. The overall design of a deep-bed filter requires balancing of many factors for which both fundamental and operating information is often lacking. The basis for choosing a granular or fibrous deep-bed filter or another type of filter is economic–a filter design should be chosen that can do a given job at the lowest total annual operating cost.

Lapple (1954, p. 115) gives comparative data in Table 8.4 for a typical deep-bed sand filter and glass-fiber filter, each with an air-handling capacity of 35,000 cfm. The sand filter has 9-1/2 ft of graded sand and gravel (3 in. to 50 mesh) supported on a ceramic-tile air distributor. The fibrous filter has a 9-ft total depth of graded glass-fiber layers (Lapple, 1954, p. 116); each layer is separately supported by a screen and there is a screen on top of the final layer of Type AA "Fiberglas." The filter beds are horizontal, with air flowing vertically upward through them. The filter sizes given (in Table 8.4) include the filter housing proper and inlet and outlet air manifolds, but not lead-in or exhaust ductwork. Cost estimates for the sand filter are based on actual construction costs of an operating unit, corrected to a 35,000-cfm capacity. The Fiberglas data are estimated for a specific design having the above capacity, based on the work of Blasewitz *et al.* (1951, Parts 1 and 2). The housing cost includes excavation, concrete structure, roofing, drains, painting, duct connections, etc. The cost of the filter medium includes the cost of tile distributor blocks as well as the cost of sand and gravel in place. The cost data for these filters in Table 8.4 (Lapple, 1954, p. 115) are based on information available in 1952. For the two filters to be truly comparable, the pressure drop, collection efficiency, and life should be the same. This could be achieved approximately by halving the size of the glass-fiber unit and eliminating some of the finer fibers. The cost comparison would then be even more favorable for the glass-fiber filter.

Zahn (1953) made a detailed cost comparison of a sand and fibrous-glass bed with 126,000-cfm capacity when the ventilation system for the Hanford Purex Plant was being designed. Based on the data given in Table 8.4, conclusions of the study are as follows:

1. Use of fibrous-glass filter would reduce total cost of the project about $520,000.

2. Initial pressure drop through fibrous glass is ~3 in. less than for a sand filter.

3. Collection efficiency of a fibrous-glass filter is 99.9%; that for a sand filter is 99.5%.

4. The plot area is considerably smaller for a glass-fiber filter than for a sand filter.

5. Hanford's limited experience (as of 1953) with fibrous-glass filters indicates they are entirely satisfactory. The recommendation based on this study was to use a fibrous-glass filter installation if a filter is needed in the Purex exhaust-ventilation system.

Blasewitz (1954b) made another cost comparison for the Hanford Separations Plant ventilation system. He suggested that a standby filter for emergencies or occasional high levels of activity would be the most economical solution, since it appears that the main ventilation stream from this plant can normally be discharged directly to the stack, while the vent gases from process vessels pass through high-efficiency deep-bed Fiberglas filters before entering the main ventilation stream. Table 8.4 gives cost estimates for alternative filter systems, each having a capacity of 100,000 cfm.

Table 8.4 indicates that in all cases in which equivalent sand and fiberglass filters were compared, the fiberglass filter cost is about half that for a sand filter and that the fiberglass filter takes up a fraction of the area and provides a collection efficiency of 99.9% or better, as compared with 99.5% for a sand filter. The superficial gas velocity is higher and the pressure drop lower for a fiberglass filter than for a sand filter. Such considerations led to an increasing interest and use of fiberglass filters and a diminished interest in sand filters during the following decade.

8.1.1.2 Filter-life Estimates for Hanford Sand Filters and Fiberglass Filters

As a basis for estimating the life of a large sand filter, the only related experience is with large coke beds used for collecting sulfuric acid mists. The latter last for 6-10 yr and may be washed out as often as twice a year to remove part of the accumulated material. They accumulate dust from unfiltered air, dust from sulfur burners, and sublimed sulfur; thus, the conditions of operation are much more severe than for the Hanford sand beds (Work, 1948, p. 17).

Filter life of the proposed Hanford sand beds was initially estimated by Lapple (1948a, pp. 18-19). The total particle content of gases entering the sand filter varies from 0.1 to 2.0 grains/1000 ft^3. If an average of 1 grain/1000 ft^3 is assumed, 23,000 lb of particles will be deposited during a 10-yr period in the sand filter, which contains ~1,000,000 lb of fine sand. This represents only a small percent buildup. For an overall collection efficiency of 99.99% by the filter, each layer of fine sand one grain thick is estimated to collect 1% of the particles encountering it.

Thus, 230 lb might accumulate in 10 years on the first one-sand-grain-thick layer, which weighs ~1000 lb. A noticeable increase in pressure drop for this layer would occur, with small pressure drops in subsequent layers. Since in actuality a large proportion of deposited material will be caught in the coarser supporting layers, an estimate of at least a 5-yr filter life seemed reasonable for the proposed 48' by 110-ft beds with 30,000-cfm flow rate. Adding a second unit in parallel should more than double the filter life, since a greater percentage of material would then be caught in the coarser layers and the total quantity of matter entering each filter would be halved.

Although laboratory digestion tests indicate some reaction of Hanford sand with acids and caustic, the amount of reagents likely to pass into the bed is negligible compared with the mass of the sand and no appreciable compaction of the bed is likely.

The above estimates of filter life are based almost entirely on pressure drop, since variations in collection efficiency are not likely to influence filter life. An excessive pressure drop will probably develop long before deposited matter penetrates the filter, and the usual air velocities are too low for previously deposited matter to reentrain. When the pressure drop of a sand filter becomes too high, the "plugged" filter will be left in place underground and a new unit connected into the air stream.

For applications in which the concentration of solids is much greater than that encountered at Hanford, deeper beds of coarse solids are recommended to give more holdup space for the particles collected. In the development of a sand filter for a particular application, the design should provide a reasonable life, pressure drop, and collection efficiency (Lapple, 1948b, p. 7). Thus, finer sand (<20-40 mesh) would increase collection efficiency with less sand, but would necessitate a larger bed area for a specified capacity if a filter life of reasonable length was to be obtained; the installation cost would be more dependent on the cost of the fine sand. Deep beds of a coarser grade of fine sand would allow smaller bed areas but require a greater quantity of fine sand, making the cost of fine sand the dominant economic factor. For a practical overall design giving high collection efficiency, the use of 20-40 mesh sand or other granular material, 2-6-ft bed depths, and 5-20-ft/min air velocity are believed to be about optimum (Lapple, 1948b, p. 14).

Lapple (1949b, p. 4) predicted that although the sand filters at Hanford would last at least 2-3 yr, they would eventually have to be replaced, and he recommended that commercial units such as the Hersey filter and the Cottrell precipitator should be tested, compared in terms of cost, and possibly be installed in parallel with the sand filters.

Initial tests on No. 55 Fiberglas packed to 6-lb/ft^3 density and supported directly on 8-mesh screens indicated that, for a given velocity, collection efficiency was noticeably higher and pressure drop lower than for the sands tested; thus, Fiberglas should be a more economical filter unit having a longer life (Lapple, 1949b, p. 5). Greater voidage, 96% for No. 55 Fiberglas packed 6 lb/ft^3 and 98% for AA Fiberglas as compared with 40% for sand, should result in longer filter life for the Fiberglas (Blasewitz, 1949, p. 52).

Blasewitz *et al.* (1951, Pt. 1, pp. 12-13) made an extensive investigation of glass-fiber filters as a possible future replacement for the sand filter that in 1951 had operated 2-1/2 yr with no maintenance at a 99.7% collection efficiency. A primary objective of his study was to develop a high-efficiency filter capable of operating much longer than the sand filters with no noticeable increase in pressure drop.

Initially, Blasewitz studied laboratory sand filters (see Section 7) patterned after Hanford sand beds. The first test unit (filter) was contained in a 4.5-in.-diam steel vessel; the next two test units were contained in Lucite tubes, with pressure taps at each interface between layers, as well as above and below the filter. Columns were packed by pouring in an aggregate to the desired height; however, it was difficult to reproduce pressure-drop readings on repacked columns. Superficial gas velocity of methylene blue test aerosol passing upward through a sand filter was 5-10 ft/min. The data for these tests are summarized in Table 8.5 (Blasewitz *et al.*, 1951, Pt. 1, pp. 88-89). Visual inspection of the filter column showed the greatest concentration of methylene blue near the interface of Types IV and V sand; subsequent colorimetric analyses with a spectrophotometer confirmed this. The cumulative grains of methylene blue passing into the unit per square foot of filter area were plotted against the pressure drop (Blasewitz *et al.*, 1951b, Pt. 2, p. 85), and it was observed that the resistance of Type VI sand increased from 1.25-1.50 in. of water when the first 80-90 grains/ft^2 entered the filter and then remained constant, apparently because of removal of methylene blue in the coarse layers. Types IV and V sand show definite increases in pressure drop that corresponded to increased collection efficiency, the life of the total filter being mainly dependent on the pressure drop in the Type IV sand layer.

A third test filter was designed with pressure taps at each sand layer and at each interface. Table 8.5 shows that there was a high pressure drop (6.05 in.) at the 2-in. interface of Types IV and V sand, whereas the pressure drop was 0.01-0.62 in. for other layers of the filter. The life of the filter was determined at the interface of Types IV and V sand. Another plot showed that the pressure drop for the first 50 grains/ft^2 increased from 0.06 to 0.12 in. for the IV-V interface and from 0.30 to 0.47 in. for the V-VI interface. The former pressure drop continued to rise as additional methylene blue was fed, while the latter leveled off.

The "life" of the sand-filter test units was arbitrarily set as the number of grains passing into a unit per square foot

TABLE 8.5. Life Expectancy of Test Sand Filters (Blasewitz, 1951)

	Type of Sand	Layer Depth, in.	Superf. Gas Vel, ft/min	Initial Pressure Drop, in. water	Σ Values (grains/ft²)[a] for the Indicated Increases in Pressure Drop, in. water					Shutdown Values	
					1	2	3	4	5	Pressure Drop, in. water	Grains/ft²
First Test Unit	IV	2		0.07	85.5	89.1	-	-	-	2.4	
	V	12		1.30	70.9	83.6	89.1	-	-	4.40	
	VI	3		1.80	-	-	-	-	-	2.00	
	Entire filter		10	3.17	58.2	78.2	84.5	88.2	89.1	8.80	90.0
Second Test Unit	II (1-3/4–5/8 in.)	12		-	-	-	-	-	-	-	
	III (3/4 in.–4 mesh)	12		0.02	-	-	-	-	-	-	
	IV (4–8 mesh)	6		0.06	109.5	112.5	116.4	121.7	125.9	5.0–4.95[b]	
	V (8–20 mesh)	12		0.55	-	-	-	-	-	1.35–1.25[b]	
	VI (20–40 mesh)	3		1.25	-	-	-	-	-	1.58–1.45[b]	
	Entire filter		5	1.88	96.0	108.6	114.4	118.8	122.5	7.83	131.0
Third Test Unit	II	11		-	-	-	-	-	-	-	
	II–III	2		<0.01	-	-	-	-	-	0.01	
	III	10		0.015	-	-	-	-	-	0.01	
	III–IV	2		0.01	-	-	-	-	-	0.02	
	IV	4		0.025	-	-	-	-	-	0.045	
	IV–V	2		0.06	97.5	103.0	106.8	109.3	111.7	6.05	
	V	10		0.37	-	-	-	-	-	0.55	
	V–VI	2		0.30	-	-	-	-	-	0.48	
	VI	2		0.51	-	-	-	-	-	0.62	
	Entire filter		5	1.29	90.4	101.5	105.6	108.1	110.3	7.65	114.5

[a] Σ defined as the cumulative grains of methylene blue smoke passing to the unit per square foot of filter area.
[b] The pressure drop oscillated.

TABLE 8.6. Filter Formulation for a Nonacid-carrying Air Stream (Blasewitz *et al.*, 1951)

Approximate superficial velocity: 25 ft/min
The gas stream contains varying amounts of submicron particles and has a low acid content.

Layer	Type of Fiberglas	Packing Density, lb/ft³	Bed Depth, in.	Initial Efficiency, %	Initial Pressure Drop, in. water	Life Expectancy[b] Σ, grains/ft²
Bottom	115K	0.75[a]	12	>37	<0.12	>1400
Second	115K	1.5	18	50	0.18	1400
Third	115K	3.0	12	56	0.34	362
Fourth	55Ps[c]	3.0	12	94	1.7	157
Clean-up	AA	1.2	1	99.8	2.70	28
Total			55	99.999	5.0	>1400

[a] Σ is defined as the cumulative grains of methylene blue passing to the filter layer per square foot of filter area.
[b] The shipping density of No. 115K is 1.5 lb/ft³. The value 0.75 lb/ft³ for packing density is merely nominal and indicates that the material is shredded to less than 1.5 lb/ft³. The filtration characteristics of such a layer vary in an unknown manner, since the packing density is not uniform.
[c] Number 55Ps designates No. 55P Fiberglas manufactured as a preformed mat and having as a binder the normal phenol-formaldehyde polymer with a silicone additive. The silicone addition is intended to increase the weatherability of the material without affecting the efficiency or permeability characteristics. As yet, no tests have been made; the data given are based on No. 55P experiments.

of filter area and causing a pressure drop increase of 5 in. The second and third test columns had "lives" of 122.5 and 110.3 grains/ft², respectively.

Subsequently, traverse measurements were made on one of the plant sand filters by lowering (into a monitoring tube built into the sand bed) an ionization chamber probe encased in a 3/4-in.-thick lead shield having a 1/4-in. circumferential slit. The shield restricted the readings to small layers of the filter, minimizing the counting of radiation above and below the slit. Two maxima were noted, one ~2 in. from the IV-V interface and the other 2 in. from the V-VI interface; the relative level of activity was measured as micromicroamperes. In each instance, the V-VI interface activity level was greater than at the IV-V interface. If it can be assumed that process cell air acts in a manner similar to methylene blue smoke, the plant sand filter was in an early phase of its "life" at the time of measurement. In a large sand bed, the activity level at the IV-V interface may eventually surpass that at the V-VI interface (Blasewitz *et al.*, 1951, Pt. 1, pp. 92 and 99).

Simultaneously, a series of life expectancy tests was conducted on Fiberglas columns consisting of various packing combinations of graded fibers. Specifications are given in Table 8.6 (ibid., p. 121) for a fixed-bed filter of Fiberglas designed to remove low concentrations of submicron particles when operated at a superficial gas velocity of 25 ft/min with 99.999% efficiency. This filter has an expected life of ~15 yr. The large sand beds at Hanford were believed to have a life expectancy of 6-8 yr after this series of tests (ibid., pp. 117-122).

Palmer (1956, Pt. 1, p. 67) reported that the sand filters operated satisfactorily with no maintenance, while one of

the Fiberglas fixed bed filters had plugged, requiring that the top three layers of finer-texture Fiberglas be removed manually with a pitchfork and placed in plastic bags for disposal. The latter operation was extremely costly, since each man received a maximum daily exposure in 3 min. Shutdown costs were encountered as well as labor costs; precautions were taken by the ventilation engineer to prevent (1) any reversal of flow in the building affected or (2) spreading of contamination into the area where work was being done.

Reviewing the performance of fixed-bed filters at Hanford, First (1968, p. 73) noted that sand filters had given many years (20 yr) of continuous service and might continue for many more without maintenance or replacement. A graded bed of glass fibers, 5 ft 4 in. thick, designed to be a long-lived, more efficient, and lower resistance filter than sand, operated for more than 10 years before replacement was required because it was plugged with NH_4Cl.

8.1.2 Savannah River Plant

According to Clark (1954, pp. 155-157), the basic air-cleaning philosophy at Savannah River Plant (SRP) provides for cleaning of all air streams of radioactive particulates, confining contamination to the smallest possible area, and protecting outside areas from any released contamination. Figure 8.6 shows five different types of subareas for which four different types of high-efficiency filters are used. All streams discharge through a 200-ft stack.

Subarea 5 contributes 60% of the total stack gas. The ventilation stream is filtered through a large sand filter bed patterned after Hanford's. Air entering the bottom of the bed through a clay-tile distribution system passes upward through graded filter-bed layers and finally through two "holddown" layers having a total thickness of 12 in. The total bed depth is 7 ft; operating collection efficiency is ~99.7% (ibid., pp. 158-159).

The two chemical-separations facilities at Savannah River effect recovery of unconsumed uranium from SRP reactors and separation of plutonium and special isotopes (Sykes and Harper, 1968a, 1968b). From fuel-reprocessing "canyon" buildings in F and H areas, air passes through a sand filter that removes particulate radioactivity. A process-vessel vent system consists of a dehumidifier, a heater, and a Fiberglas filter upstream from the sand filter. A portion of the air from plutonium finishing that has been triple-filtered through high-efficiency filters is exhausted directly to the stack; the remainder passes through the sand filter.

The two large sand beds (100 by 240 by 8 ft) operated satisfactorily for ~13 yr (in F area from 1954 to 1968) and in H area from 1955 to 1968 at >99% collection efficiency and (with the exception noted below) with acceptable increases in differential pressure at a superficial gas velocity of 4.7 ft/min. Airflow ranged from 100,000 to

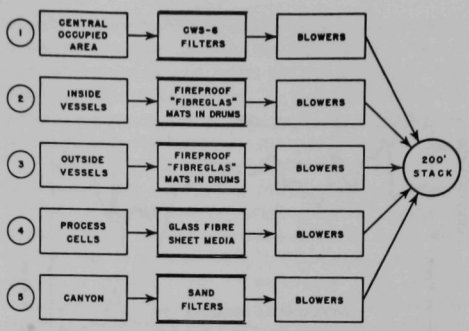


Fig. 8.6. Air-cleaning System for Particulate Removal at Savannah River Plant (Clark, 1954).

130,000 ft^3/min, variations being due to changes in differential pressure. An abrupt increase in pressure drop across the F area sand filter in 1966-1967 instigated a search for its cause. Refined flow-rate, pressure-differential, and dew-point measurements indicated that there was excessive moisture in the bed. Cracks in the concrete side walls of the bed (above the layer of 1/4-in. gravel) had allowed ground water to enter, as was indicated also by stains on the walls. A 3-in. settling of the bed was noted. Earth was excavated from around the walls and all cracks were repaired, but no backfilling to prevent future leaks was done. Efforts to dry the sand by heating were limited because a maximum temperature was imposed by process restrictions; however, the pressure drop was 15% lower after several months.

Dust accumulation was ~2 lb/day. Its source was dust that passed through the canyon inlet air filters and dust from slow deterioration of concrete. Although the dust acted as a filter aid, it also contributed to increased differential pressure.

Activity measurements (Sykes and Harper, 1968b) indicated that about 1000 Ci of gamma activity was in the bed; activity had penetrated only to the finest (30-50 mesh) sand. About 1000-2000 Ci of gamma emitters (principally Ce, R, Zr, Nb) entered the filter annually. Curves in Figs. 8.7 and 8.8 show differential pressure changes. Figures 5.1 and 8.9-8.11 show radioactivity at various locations in the sand filter and at various times.

Figures 8.9-8.11 indicate that filter collection efficiency improved with time. Figure 8.11 indicates that radioactivity release is a function of two variables—filter inventory and instantaneous input; also, release from a new filter cannot be predicted from experience with an operating filter. No cost estimates have been found in the literature for the large sand-filter beds at Savannah River (Sykes and Harper, 1968).

Recently, it was reported that the mortar in the tile air-distribution system had deteriorated from acid attack and that one of the Savannah River sand filters had partially collapsed (Curren and Koontz, 1969).

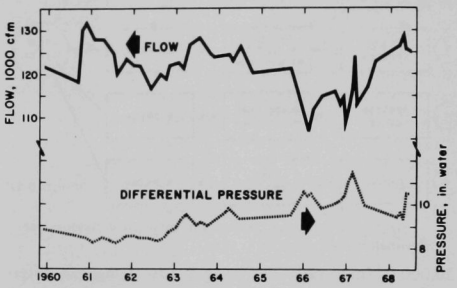


Fig. 8.7. Filter Differential Pressure Changes in Savannah River Sand Filter (Sykes and Harper, 1968b).

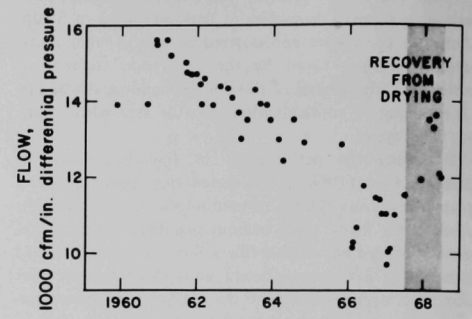


Fig. 8.8. Flow in Savannah River Sand Filter (Sykes and Harper, 1968b).

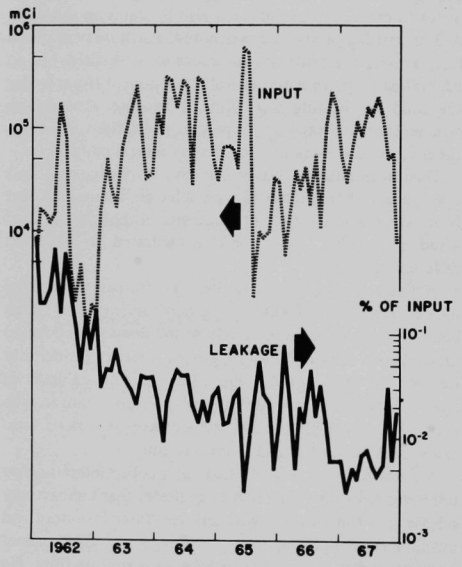


Fig. 8.9. Beta-Gamma Activity Input and Leakage (Sykes and Harper, 1968b).

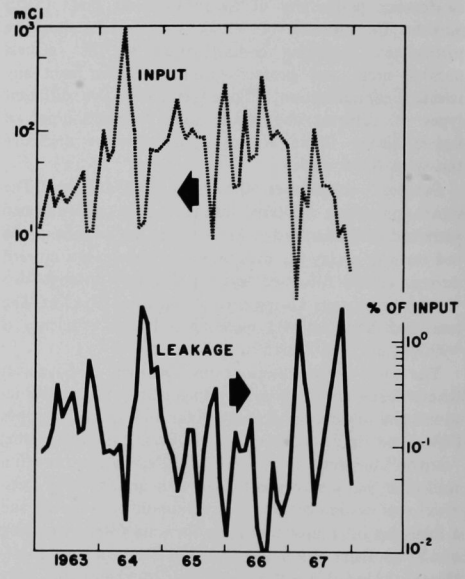


Fig. 8.10. Alpha Activity Input and Leakage (Sykes and Harper, 1968b).

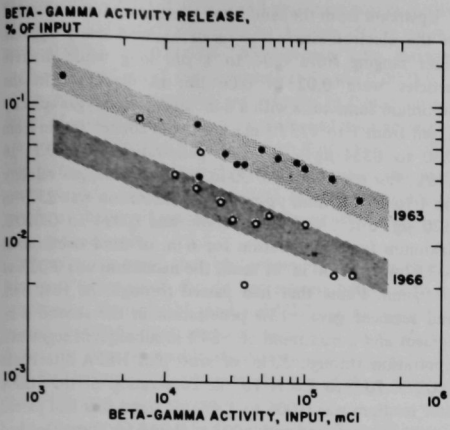


Fig. 8.11. Beta-Gamma Activity Filtration Improvement (Sykes and Harper, 1968b).

8.2 OTHER INSTALLATIONS

8.2.1 Zero Power Plutonium Reactor

The Zero Power Plutonium Reactor (ZPPR) constructed at the National Reactor Testing Station in Idaho was designed under the supervision of the Idaho Division of Argonne National Laboratory. The largest fast-reactor critical assembly in the United States, it will be used primarily to study the physics characteristics of plutonium-fueled power breeder reactors for central stations in the range of 1000 MWe. Although the reactor cores may contain as much as 3000 kg of plutonium for some studies, the power levels are generally less than 100 W. A reactor core will consist of two halves on separate tables, each assembled separately; bringing the two halves slowly together completes the core. Final criticality is reached by slowly inserting fuel-bearing control rods (Lawroski, 1968).

The reactor cell is a cylinder 50 ft in diameter and 23 ft high having walls and floor of heavy reinforced concrete. The cell roof, designed for safety purposes, consists of alternate layers of sand and gravel as shown in Fig. 8.12 (ibid., p. 49). It is supported by 1-7/8-in.-diam steel cables, forming a catenary cable network with 15-in. centers. Cables are threaded through a ring beam 7 ft wide and 5 ft thick; several layers of overlapping wire mesh are placed on the cable network to support the lowest gravel layer. Two layers, 1 and 1-1/2 ft thick, of washed and dried 20-50 mesh sand provide a high-efficiency particulate filter. Sand is supported on 26- by 26-mesh by 0.017-in. woven wire cloth. The thickness of the sand and gravel roof varies from 16 ft at the periphery to 21 ft at the center of the cell. Estimated minimum attenuation of airborne particulates is 3×10^3 through the sand and gravel roof. A compacted earth fill at least 10 ft deep surrounds the reactor cell and adjacent rooms and corridors. Directly above the cell roof is a backup containment structure consisting of 288 AEC-type high-efficiency filters mounted on the periphery of a huge filter housing (ibid., p. 49). The design of the gravel and sand roof combined with the backup containment gives an overall airborne particulate attenuation of 10^6 for the reactor cell.

Filtration tests with the type of sand to be used in the Zero Power Plutonium Reactor (ZPPR) roof of sand and gravel were made by Cheever *et al.* (1967) of the Industrial

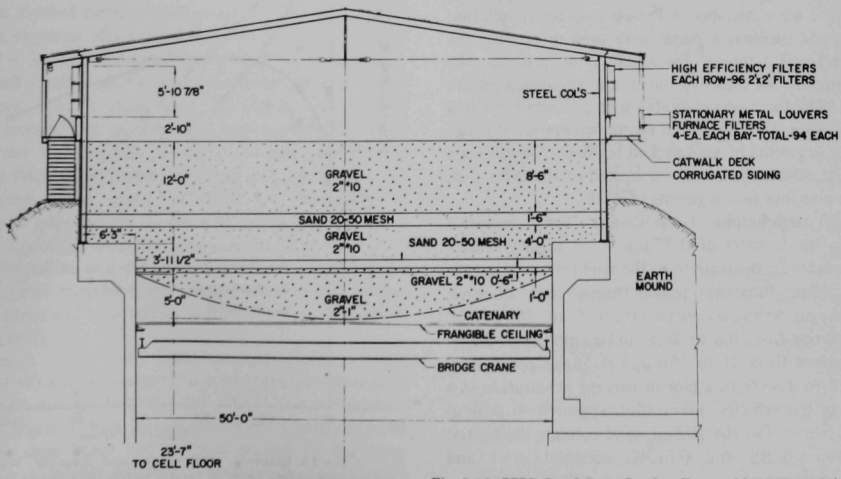


Fig. 8.12. ZPPR Roof Cross Section (Lawroski, 1968, p. 49).

Hygiene and Safety Division at Argonne National Laboratory. The roof will act as a heat sink and as a highly efficient particulate filter in a high-volume filtration system. Under accident conditions, the roof would minimize the escape of plutonium aerosols and relieve gas pressure from the reactor cell. The cost is lower than that of a conventional containment structure (ibid., p. 942).

Uranium, plutonium, and uranine aerosols were used in the tests to determine the effectiveness of the proposed filtration system. Uranium fume was tested first as a stand-in, since it is much less hazardous than plutonium aerosol; these tests simulated pressure conditions encountered in a major accident, including lifting of the sand and gravel roof. The tests with plutonium were carried out using the plutonium fuel alloy proposed for ZPPR; plutonium fume was generated by means of a plasma torch at the high temperatures that could be encountered in a reactor accident. The uranine aerosol was tested at velocities and concentrations suitable for in-place testing of the sand and gravel roof.

The sand used in all tests was the same irregular-grain type as was to be used in the ZPPR roof. Superficial gas velocities were corrected to standard temperature and pressure. Millipore Type AA filters (0.8-μm pore size) were used as sampling filters, with HEPA downstream filters also being tested in some cases. Electron-microscope grid samples were used in particle-size determinations.

The uranium test apparatus was of standard copper tubing and fittings with soldered joints; a 2-in.-diam column had a 29.5-in. sand depth, a 1-in.-diam column had a 6-in. sand depth. Uranium turnings were burned on a red-hot Nichrome coil in a glass burn chamber below the column. Dry compressed air carried the fume to the column. The uranine aerosol tests were carried out in the same apparatus without the burn chamber; a Pen-i-sol nebulizer, dilution chamber, and diaphragm pump were used to produce the aerosol and pass it through the column under pressure. The plutonium tests were carried out in a nitrogen-atmosphere glovebox. The fume was generated with a plasma torch in a small enclosure at >3100°C and was drawn upward through three 2-in. segments of sand packed between 60-mesh brass screen; the 30-in. sand column consisted of the three 2-in. segments plus four 6-in. segments of sand.

Electron micrographs of the uranium fume showed a count median diameter of 0.07 μm and a slightly smaller size in samples downstream from the sand filters. In tests in which uranium fume was passed through 6 in. of sand, superficial gas velocities varied from 5 to 200 ft/min, pressure drops from 0.6 to 28.5 cm Hg, upstream sample concentrations from 21 to 156 μg U/ft^3, and penetration from 0.22 to 1.45%. In a plot of percent penetration as a function of gas velocity, penetration appeared to peak at about 60 ft/min. For the 29.5-in. sand column, the highest penetrations, 0.015 and 0.013%, occurred at 1 and 10 ft/min, respectively.

Upstream from the sand filter, plutonium fume observed on the electron-microscope grids showed many agglomerates ranging from 0.04 to 1 μm long while discrete particles were 0.02 to 0.06 μm in diameter. In the plutonium fume tests with a 6-in. sand column, gas velocity ranged from 1 to 133 ft/min, upstream concentration from 1230 to 6334 μg Pu/ft^3, and penetration from 0.11 to 0.76%. For tests with the 30-in. sand column, gas velocity was 1 to 28.3 ft/min, upstream concentration was 2379 to 3120 μg Pu/ft^3, and penetration was 0.004 to 0.020%. Maximum fume penetration for 6 in. of sand occurred at ~60 ft/min; for 30 in. of sand, the maximum was 0.02% at 4.8 ft/min. Fume that had passed through the first 6-in. sand segment gave ~13% penetration in the second 6-in. segment and a maximum of ~84% in subsequent segments. Penetration through 30 in. of sand plus HEPA filters was 0.002×10^{-4} to 1.6×10^{-4}%. Penetration of the HEPA filter medium was 0.006 to 1.4% for fume that had passed through 6 in. of sand and 0.003 to 0.99% for fume that had passed through 30 in. of sand.

The electron micrographs gave a count median diameter of 0.1 μm for uranine aerosol and a calculated mass mean diameter of 0.59 μm. In uranine aerosol tests at superficial

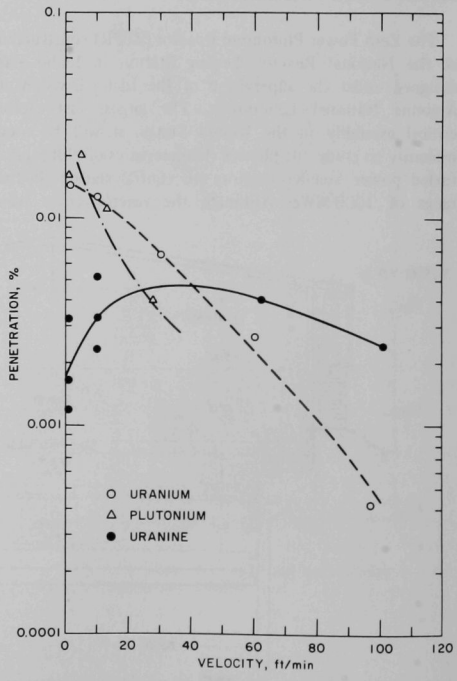


Fig. 8.13. Uranium, Plutonium, and Uranine Penetration through Nominal 30 in. of Sand (Cheever *et al.*, 1967, p. 963).

gas velocities of 1-101 ft/min and upstream concentrations of 15.7 to 204 $\mu g/ft^3$, penetrations through 29.5 in. of sand were 0.0012 to 0.0052%. At 1 ft/min (the proposed in-place test velocity), average penetration was 0.0021%.

Percent penetration and gas velocity in ft/min through 30 in. of sand for uranium, plutonium, and uranine aerosols are compared in Fig. 8.13 (Cheever *et al.*, 1967, p. 963). The penetration-vs-velocity data for uranium and plutonium aerosols are similar; uranine aerosol penetration is within an order of magnitude of the penetration for the other two aerosols.

Conclusions were that plutonium penetration through the sand filter alone should not exceed 0.02%, and that penetration through the sand and HEPA filters should not exceed 0.0001%; that uranium burned in air produced a fume that is a reasonable stand-in for plutonium aerosol; and that uranine aerosol is suitable for in-place testing of the ZPPR sand and gravel roof.

McFee and Sedlet (1968) presented a detailed account of plutonium alloy fume tests done for the preliminary safety analysis of ZPPR. The composition of the fuel alloy was 24.3% plutonium, 73.2% uranium, and 2.5% molybdenum. The penetration tests described are essentially those reported by Cheever *et al.* (1967); results are summarized in Fig. 8.14. However, also reported is a reentrainment test (run after filtration tests had been completed) to determine the possibility of fume being released by alpha recoil or other mechanisms. The first 2 in. of sand from a previous filtration test, which contained plutonium with an activity of 7.7×10^8 dpm, was transferred to a clean tube and backed with 2 in. of fresh sand and a Millipore filter. For a total of 164 hr, the air was drawn through the filter at 31 ft/min.

The Millipore filter that was changed after the first half-hour showed material with an activity of only 7.5 dpm released; exposure of a second Millipore filter for 163.5 hr resulted in another 7.4 dpm being released, showing that a very small fraction of the plutonium was reentrained and penetrated 2 in. of clean sand. No doubt, most of the activity released was on very small sand particles produced during the transfer and located near the downstream interface (McFee and Sedlet, 1968, pp. 643 and 646).

Although some areas of fume on the electron-microscope grids had no electron-diffraction pattern, other areas had good patterns, showing that the fumes consisted of polycrystalline and noncrystalline oxides of plutonium, uranium, and molybdenum. Compositions varied within specific areas and also within samples (McFee and Sedlet, 1968, p. 647).

Although this study (McFee and Sedlet, 1968, pp. 647-649) was not designed to study variables other than penetration and gas velocity, the effect of other variables such as pressure drop was noted. With well-mixed sand from the same batch and columns packed by the same procedure, a notable variation in pressure drop occurred at

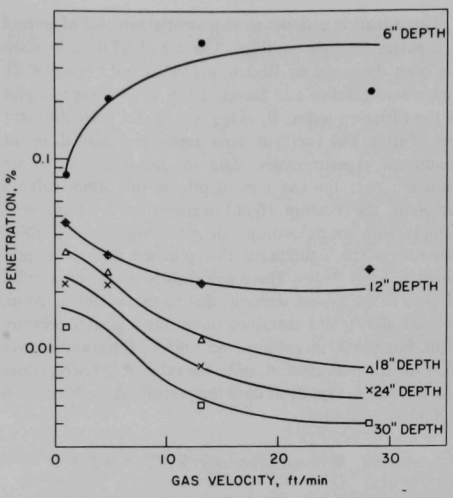


Fig. 8.14. Penetration vs Velocity through Different Depths of Sand (McFee and Sedlet, 1968, p. 647).

different gas velocities. A filtration index, relating the amount of filtration to pressure drop, can be given as

$$F = \frac{-\ln (N/N_0)}{\Delta p}$$

where

F = an index of filtration,

N/N_0 = the fraction of aerosol penetrating the filter, and

Δp = pressure drop across the sand.

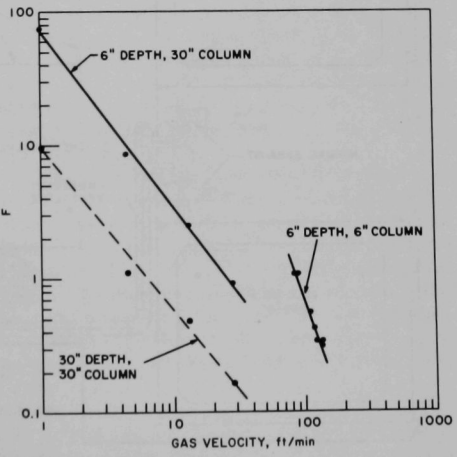


Fig. 8.15. Index of Filtration, $F = -\ln (N/N_0)/\Delta p$, vs Gas Velocity (McFee and Sedlet, 1968, p. 649).

This equation assumes an exponential removal of aerosol as it passes through the filter. The use of a filtration index has been discussed by Rodebush (1950) and Chen (1955). Figure 8.15 (McFee and Sedlet, 1968, p. 649) shows a plot of the filtration index, F, vs gas velocity for three different sets of data. The two 6-in. sand depths represent different conditions experimentally; data for the 6-in. column are "actual"; data for the 6-in. depth of the 30-in. column represent the bottom (6-in.) segment of a 30-in. sand column with pressure drop calculated from the full 30-in. column on the assumption that pressure drop is proportional to sand depth. There was slightly more compaction of sand in the lowest segment, due to the weight of 24 in. of sand above, and therefore there was a greater pressure drop. For the 30-in. column, the index of filtration is lower than for the 6-in. column, since the value of $\ln (N/N_0)$ does not increase as rapidly as does the pressure drop, between 6 and 30 in. of sand.

8.2.2 Argonne National Laboratory's ZPR-6 and -9

The national LMFBR program needs integral experimental physics data for large dilute plutonium-fueled fast reactors. ZPR-6 and -9, two split-table type critical facilities, were modified so that they could be used to obtain such data. Modifications included a confinement shell constructed over the reactor cells and the addition of an

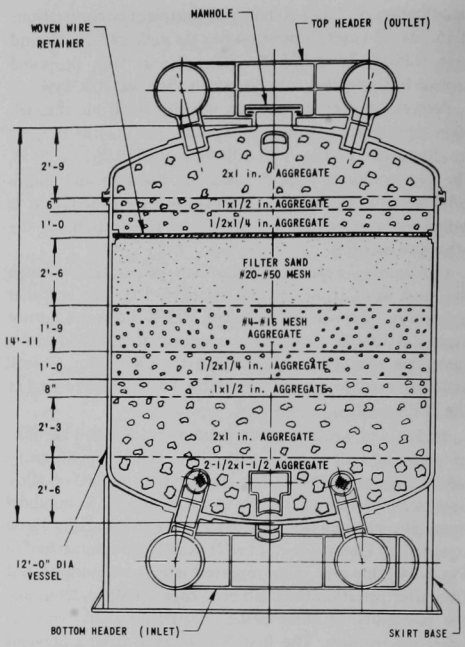


Fig. 8.17. Sand Filter (Kato *et al.*, 1968).

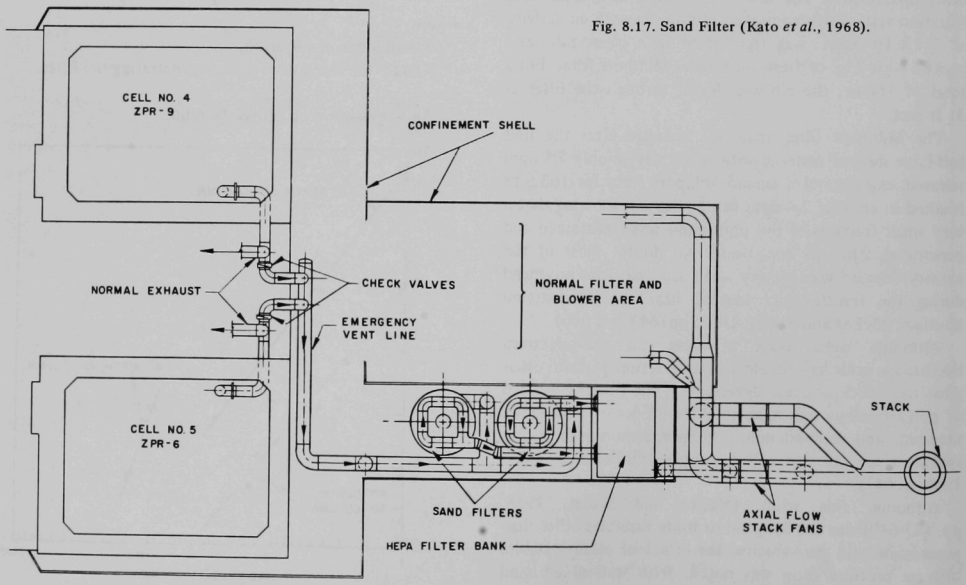


Fig. 8.16. Venting System (plan view) (Kato *et al.*, 1968).

emergency sand filter exhaust system (Kato *et al.*, 1968, p. 1). Among the main elements of the containment concept were the following:

1. Primary containment by the original blast-resistant reinforced concrete walls.

2. Collection of any gaseous or particulate leakage (from the reactor cells) in a confinement shell maintained at subatmospheric pressure.

3. An emergency venting system for the cells—a sand filter, two banks of HEPA filters, and a 46-m stack—to maintain cell integrity even if there is a large rise in cell pressure as in the event of a serious accident.

4. Provision for discharging effluents from the confinement shell volume, from emergency venting, and from normal air conditioning in the cell, control room, vault, and vault workrooms through an exhaust system of HEPA filter banks and a 46-m stack in series.

The cell and the confinement shell are designed to protect against the external consequences of a nuclear incident, and the sand-filter system is designed to protect against the compounding effects of a severe metal fire or a fire alone (ibid., pp. 3-4).

Differential pressure switches that measure variations in air pressure are located at 49 positions in the shell, including three positions at the sand filter. During reactor operation, the confinement-shell atmosphere will be kept at a pressure of 0.994 bar (-2.5 in. of water with respect to the atmosphere) to prevent particulate matter from escaping to the atmosphere in the event of a nuclear accident.

The confinement shell, constructed of plate steel (0.47 cm or 3/16 in.) welded on a structural steel frame and supported on existing columns and on new footings, encloses the south portion of Building 316-W at Argonne National Laboratory, including both reactor cells, the loading dock, the existing vault, the new vault, and the sand and HEPA filters for the emergency venting system. This shell can withstand a snow load of 30 lb/ft^2 on the roof, a wind load of 30 lb/ft^2 on vertical surfaces (equivalent to a wind velocity of ~177 km/hr or 110 mph), an exhaust differential load of 5 lb/ft^2 on all surfaces, and a total load of 35 lb/ft^2 on all surfaces. The confinement shell is sealed to existing building surfaces, except at below-grade portions, and is designed to maintain the structural integrity under normal rapidly varying atmospheric pressures, access to the shell being through air-lock doors. An air space of 1.2 m (40 in.) between the shell and existing cells and vault is also kept at 0.994 bar (-2.5 in. of water) with respect to the outside atmosphere during reactor operation (ibid., pp. 123-127).

The emergency exhaust system, designed for rapid relief of cell pressure buildup in case of a rapid metal fire, is shown in plan view in Fig. 8.16 (ibid., p. 134). Its basic components are a 24-in.-diam exhaust pipe bypassing the normal exhaust system and connected to a sand filter and a double bank of HEPA filters. Also important are the check valves (one-way, spring-loaded, silicon rubber-seated valves), which allow one-way gas flow with little backflow. Thus, one cell can be rapidly vented to the sand filter while no contaminated gas enters the other cell.

Two large sand filters were constructed to act as a heat sink for hot gases and to remove particulate matter; one is shown in Fig. 8.17 (ibid., p. 138). The filters are contained in 12-ft-diam tanks with 2.5-m depth of successively finer aggregate supporting a 75-cm (30-in.) layer of 20-50 mesh sand. The sand filters are installed in parallel, and each has a capacity of ~5700 liters/sec or 12,000 cfm of air with a pressure drop of 0.7 bar or 10 psi. The maximum total capacity is thus ~11,000 liters/sec or 24,000 cfm with a 0.7-bar or 10-psi pressure drop. With ~148 tons of sand in the two filters and an assumed specific heat of 0.2 cal/(g)(°C) for sand, the heat capacity of the sand filters is $\sim 2.6 \times 10^7$ cal/°C. Initial heat releases up to 1.3×10^7 cal/sec, with a maximum of 20-psig pressure, could be handled by the emergency exhaust system.

Tests described later in this section showed attenuations of 10^3-10^4 for particles in the range of 0.02-0.06 μm and greater attenuations for larger particles at flow rates up to 10 m/sec or 200 ft/min. For 30 in. of sand plus AEC-type filters, attenuation factors of 10^6 were attained; factors of 10^7 and 10^8 are estimated if another HEPA filter bank is added. The sand filters in the emergency exhaust system were backed up with two banks of HEPA filters (ibid., pp. 133-140).

No provision was made to remove noble gases or volatile radioiodine in the emergency exhaust system (ibid., p. 140).

An argon purge system is provided to decrease the available-oxygen level from 20 to 1% and thereby minimize combustion in the event of metal fires from uranium, plutonium, or sodium. High-pressure tanks containing 3.4×10^6 liters of argon gas are located outside the reactor facility. Introduction of this amount of argon at 36,000 cfm initially and at an average rate of 6000 cfm would decrease the oxygen content in the cells to ~1% in about 20 min (ibid., p. 140).

To obtain data related to the addition of a sand filter and other modifications in containment systems (necessitated by the use of plutonium fuels in the ZPR-6 and -9 reactors), a sand-filter test column was operated. The filtration efficiency and percent penetration were determined, using fluorescent and uranium aerosols. The column was loaded with 21 in. of 4-16 mesh Connecticut aggregate, 30 in. of 20-50 mesh Idaho sand, and a layer of larger aggregates to make a total 15-ft depth (Kato *et al.*, 1968, p. 296).

In the first test, fluorescein aerosol was generated from a 0.5% solution of fluorescein-free acid in ethanol at a pressure of 30 psig, using a standard Collison atomizer nozzle plus an impactor with five 1.5-mm-diam holes. This solid aerosol of submicron size was collected on Type AA

membrane filters in disposable plastic holders, and quantities as small as ~0.0001 μg were analyzed by fluorescence; samples were taken upstream of the filters by electrostatic precipitation for electron-microscope photographs. The rate of generating the aerosol was 700 μg/min (within a factor of two). Test results showed that the percent penetration at 1-ft/min gas velocity decreased during the course of the run—from 2.4×10^{-3} initially to about 5.2×10^{-5} after 20 tests; maximum penetration of 0.104% occurred at a velocity of 103 cfm. Penetration is expected to be <0.01% for this aerosol for velocities of 1-10 ft/min, but may be as high as 0.1% at higher velocities (ibid., pp. 295-299).

In the uranium-aerosol penetration tests, Idaho sand (20-50 mesh) was used along with 4-16 mesh Eau Claire aggregate. The test aerosol was obtained by burning uranium turnings on a Nichrome heating coil in a holder inside a steel chamber gasketed to the inlet-air system. Samples were obtained simultaneously on Type AA membrane filters upstream and downstream from the sand filters and were analyzed fluorometrically for uranium at concentrations as low as ~0.02 μg. Electron-microscope photographs were made as before, of samples taken upstream from the filter. The highest result for any test run was 0.177% penetration at 149 ft/min; another test gave 3.50×10^{-2}% penetration at 152 ft/min. The sand filter should provide a decontamination factor of $\geqslant 10^3$ with this uranium aerosol; in earlier tests for this uranium aerosol results were similar to those for plutonium test aerosols generated with a plasma torch. High flow rates were maintained much longer in these tests than would occur in a reactor cell accident or even with complete discharge of the cell atmosphere. A problem when changing from high-velocity to low-velocity runs was recontamination from uranium that deposited in the system. The results obtained are for tests with different sizes of aerosols and for tests with the amount of aerosol particles increasing as the tests progressed; therefore, no curves were drawn.

Fluorescein penetration tests were run on this test column for comparison purposes. Penetration ranged from 3.74×10^{-2} to 3.61×10^{-5}% at a gas velocity of 1 ft/min. The pressure-drop-vs-flow tests for the uranium-aerosol penetration-test column loading were 1590 cfm/psi per 12-ft-diam sand filter as compared with 1210 cfm/psi per 12-ft-diam sand filter for the fluorescein-aerosol penetration-test column loading used for the fluorescein-aerosol penetration tests. The column used in the uranium-aerosol tests had 388 lb of sand and aggregate above the bottom of the sand; the average density was ~105 lb/ft^3 (volume = 7.5 ft × 0.492 ft^2). The pressure-drop-vs flow tests showed that most of the pressure drop was in the sand at a flow of ~14 ft/(min)(psig). At 150 ft/min, the lifting pressure at the bottom of the sand about equaled the weight of the material above the bottom of the sand. If a flow rate of 200 ft/min were used, some fluidization might occur, but would be limited by the screen and the tightness of packing in the column (Kato *et al.*, 1968, pp. 299-303).

Kato *et al.* (1968) reported their final safety analysis on the use of plutonium in ZPR-6 and -9. They outlined the program and hazards associated with the use of plutonium fuels in these experimental reactor facilities, which had been successfully operated by highly trained and skilled personnel since 1963 and 1964 with uranium-fueled large dilute fast cores.

A maximum credible accident (MCA) was postulated in which a prompt critical excursion would occur at intermediate table speed with only the high-level trips working. For a 50-liter core, 2.2×10^{17} fissions would occur and the fuel temperature would rise 230°C; for a 3500-liter core, the corresponding values are 3.8×10^{17} fissions and 57°C. However, fuel elements would remain intact, and no activity would be released to the atmosphere (ibid., pp. 266-267).

A design basis accident (DBA) was hypothesized in which the events of the MCA (described above) would occur plus complete failure of all nuclear instrumentation and safety circuits, total disregard for the reactor condition by the operator, and continuous addition of reactivity. Such an improbable DBA would cause the release of 2.7×10^{20} total fissions, the burning of 60 kg of plutonium, and the vaporization and rapid oxidation of ~22 kg of sodium (ibid.).

In such a postulated accident, which would involve burning liquid fuel and sodium and partly vaporized sodium, a flow rate of 2400 cfm/psig was assumed for the cell air exhausting through the sand filters. This value is considerably lower than the 3200 cfm/psig obtained in a scaled mockup with the same sand as is used in the large sand filters (ibid., p. 225).

Note that energy is added and cell pressure is increased by burning molten metal such as sodium. However, the sodium burns rapidly resulting in a higher than actual heat addition to the cell and an abrupt drop in pressure so that argon gas can be injected to extinguish the fire. A cell pressure less than 3 psig results in enough flow through the sand filter to cause a decreasing cell pressure (ibid., p. 256).

In an accident in which is is assumed that 60 kg of plutonium burns in 1 hr, the calculated maximum amount released through the emergency venting system to the atmosphere is 60×10^6 mg/10^7 attenuation factor = 6.0 mg. If another 0.15 mg is estimated to leak through the cell walls and pass through the filters and the stack, a total release of 6.2 mg of plutonium is obtained (ibid., p. 259).

Body burdens of $2.6\ 10^{-4}$ μCi occur 225 m from the stack under fumigation conditions with the release of 6.2 mg of plutonium. With low wind velocity, an assumed 100% instantaneous release of noble gas and radioiodine with no cell holdup would result in doses of 190 rem 225 m from the stack and 13 rem 1500 m from the stack.

It was concluded that, with the modifications and safety practices described, ZPR-6 and -9 could be operated at

Argonne National Laboratory with plutonium fuels without undue risk to the general public or to Laboratory personnel in the vicinity (ibid., p. 267).

8.2.3 General Electric Midwest Fuel Recovery Plant

The Midwest Fuel Recovery Plant (MFRP) being constructed by General Electric (*Design and Analysis, Midwest Fuel Recovery Plant*, 1966) near Morris, Illinois, will be capable of processing 300 tons/yr of irradiated uranium as compacted UO_2 (up to 5% ^{235}U) clad in stainless steel or zirconium alloy. Spent fuels will be from light-water-moderated and-cooled power reactors. Uranium, plutonium, and neptunium will be recovered by the Aquafluor process, which consists of unit systems involving mechanical disassembly, chemical leaching, solvent extraction, ion exchange, and fluid-bed fluorination.

All equipment and systems that handle radioactive materials are housed in the main process building. A sand filter is located east of the process building with 25-30 ft between adjacent walls of the two buildings; an underground reinforced-concrete duct connects the filter to the process building. A discharge duct from the filter runs below grade to the process building and then vertically up the end of the building to the base of the exhaust stack. The stack is mounted on the roof near the east end of the process building (*Design and Analysis, Midwest Fuel Recovery Plant*, Amendment 3, 1967, p. 4-1).

The sand filter was incorporated into the ventilation system on the basis of 15 yr of operating experience at AEC chemical plants, where operations involving moisture saturation, large-scale uranium fires, etc., have caused no detectable degeneration in operating characteristics or collection efficiency of sand filters, while filter maintenance, disposal, and auxiliary safety problems have been at a minimum. Sand filters can be readily monitored and have a relatively high resistance to mechanical damage from earthquakes and tornadoes.

The sand filter is contained within reinforced concrete walls ~80 ft long, 74 ft wide, 13.5 ft high, and 1 ft thick (*Design and Analysis, Midwest Fuel Recovery Plant*, Supp. I, Sect. IV, p. 8). The filter of graded sand and gravel occupies about 80% of the filter building. The remaining space contains: a criticality emergency exhauster with filter, scrubber, and pump; three electric exhaust fans; air compressors, dryer, and auxiliary equipment; emergency generator; and inlet and outlet connections for replacement filter systems. Thus, all equipment needed for continuous operation of the exhaust ventilation system is housed within a reinforced concrete structure.

Air is drawn upward through the sand filter by exhaust fans that discharge to the stack. The filter bed and the duct from the process building are under negative pressure. Incoming air enters at the bottom of the sand filter and is distributed through radially arranged pipes or tiles in the filter floor, which also has provision for drainage. The air then passes upward through gravel and sand layers, graded as follows:

Layer Depth	Size of Gravel or Sand
1-3 ft (bottom)	100% pass 3 in., 96% on 1 in.
12 in.	100% pass 1-3/4 in., 100% on 5/8 in.
12 in.	100% pass 3/8 in., 100% on No. 3 mesh
6 in.	95% pass No. 4 mesh, 95% on No. 8 mesh
6 in.	95% pass No. 8 mesh, 95% on No. 20 mesh
3 ft	98% pass No. 20 mesh, 98% on No. 50 mesh, 30-50% retained on No. 30 mesh
6 in. (top)	95% pass No. 8 mesh, 95% on No. 20 mesh

Monitor tubes are located at each corner of the sand bed, and one is near the center. Air exits at the top of the sand filter through the exhaust duct to the stack for final discharge. The exhaust stack (3-4 ft in diameter) is an all-welded metal unit of stainless steel or with a stainless steel-clad interior. Standing 300 ft above grade and supported by a structural steel tower similar to an oil derrick, it should meet earthquake and tornado requirements. The ductwork and stack will operate with a pressure slightly more positive than atmospheric, with fans discharging about 3500 linear ft/min (*Design and Analysis, Midwest Fuel Recovery Plant*, Amendment 3, 1967, pp. 4-1 and 4-2, and Fig. III).

Radioactive gases and vapors from process equipment are conducted to off-gas treatment facilities, where particulates are 99.9% removed by passage through glass-fiber filters and halogens are 99.5% removed by caustic scrubbing and reaction with silver nitrate. Gases then pass into the ventilation exhaust tunnel and through a graduated Hanford-type sand filter in a below-grade concrete structure before discharge to the stack. The estimated stack release rates and probable percentages of maximum permissible concentration (MPC), based on proposed plant design and operation, are given below for various gaseous isotopes and for radioactive particulates.

Type of Radioactivity	Expected Stack Release Rate	Probable Percentage of MPC
^{85}Kr	<0.1 Ci/sec	~2
^{131}I	~0.1 μCi/sec	~2
Tritium	<0.005 Ci/sec	~0.1
Particulates	~0.0002 Ci/day	<1

Noncondensables from all the process concentrator condensers exhaust from the condenser vent subheader, while offgases from the leacher system and all canyon vessels in the aqueous process system exhaust from the vessel-vent subheader; both these exhausts pass through the process vent system, which consists of a caustic scrubber to

remove iodine and ruthenium, a heater and silver nitrate tower to remove backup iodine, and a glass-fiber filter to remove radioactive particulates. Monitoring of the process-vent system gas stream is especially important since this gas stream can carry ~99% of the radioactivity discharged to the sand filter in a volume of air representing only 1-2% of the total air released from the stack. Particulates are collected on a prefilter tape and measured for alpha and beta-gamma activities. Radioactive iodine is collected on an absorption filter; ^{85}Kr and tritium are also monitored. The stack is continuously monitored in a similar way.

The sand-filter inlet monitor measures alpha and beta-gamma particulate activity. Special filter samples are taken upstream and downstream from the glass-fiber filters on the vent headers and upstream and downstream from the final sand filter. Tritium in the gaseous effluent is determined by determining tritium in condensed water from the air in the process vent header and measuring dew point and airflow. The monitor system on the process vent header can quickly indicate an unusual process condition, while any unusual quantities of radioactivity entering the sand filter are indicated by the continuous sand filter monitor; both can indicate abnormal conditions much sooner than the stack monitor (*Design and Analysis, Midwest Fuel Recovery Plant,* 1966).

The ventilation system (a flow diagram of which is shown in Fig. 8.18) is a once-through system with airflow from lower to higher regions of contamination and with all building-ventilation air passing through a sand filter prior to stack discharge. With an emergency ventilation system in operation, the normal ventilating system is shut down, the canyon airflow through the sand filter greatly reduced, and the gases passed through a liquid scrubber, charcoal bed, and absolute filter before stack discharge. Gaseous effluents are continuously monitored for noble gas, halogen, tritium, and particulate radioactivity.

The sand filter is expected to minimize the effects of conditions arising in normal operations and in emergencies as follows:

1. Possible blowback into personnel zones or criticality, in the event of a large UF_6 release, would be avoided by venting the loadout enclosures to the sand filter discharge.

2. Any airborne particulate activity from a leak in waste-processing equipment would be contained by the sand filter.

3. The sand filter acts as a final filter for all off-gas treatment systems, which are maintained at slight negative pressure so that any leakage is into the systems.

4. Should a glass-fiber filter fail in the off-gas treatment system, most of the activity would be removed by the sand filter, which is expected to remove particles greater than 10 μm with a 99.97% collection efficiency.

5. Airborne contaminants and hazardous chemicals released as a result of laboratory analyses in hoods and gloveboxes are collected in the sand filter.

6. Backup protection for ruthenium removal from the process vents is provided by the glass-fiber filters and sand filters.

7. If accidental feeding of 12M HNO_3 to the plutonium ion-exchange unit resulted in increased pressure and charring or ignition of the resin, products of combustion would be finally contained by the sand filter. If half the resin containing 600 g of plutonium burned, about 1% or 6 g of plutonium could be released from the stack.

8. In the event of abnormal pressure buildup in the waste calciner with a 10% fission-product loss and particulate leakage, about 200 Ci/min of fission products would reach the sand filter.

9. In a glovebox fire involving solvent vapors with <0.1 g of plutonium reaching the sand filter, <1 mg of plutonium would pass through the sand filter at 99% containment. A fire in the process canyon involving 200 gal of solvent containing 1200 g of plutonium, $\sim 1.5 \times 10^{-4}$ day inventory of ruthenium and zirconium-niobium, and $\sim 1.5 \times 10^{-5}$ day inventory of all remaining fission products would probably result in ~4 g of plutonium and $< 0.5 \times 10^{-6}$ day fission-product inventory passing through the sand filter and being discharged from the stack.

10. Abnormal pressurization of the process vent system could result in ~20 Ci of activity reaching the sand filter and ~0.01 Ci of iodine being discharged to the atmosphere (*Design and Analysis, Midwest Fuel Recovery Plant,* 1966).

Dynamic earthquake analyses were conducted (see Fig. 8.19) with respect to the sand filter, vaults, tanks, and ducts for the Midwest Fuel Recovery Plant at Morris, Illinois (*Design and Analysis, Midwest Fuel Recovery Plant,* Supplement I, 1969, Sect. IV, pp. 1-14). The sand filter is supported on rock and is surrounded by an earth berm; vaults, tanks, and ducts are embedded in solid rock; all are constructed of reinforced concrete.

The design earthquake consisted of the North-South component of the 1940 El Centro earthquake normalized to 0.10 g. The filter structure, the filter material, and the earth berm of the sand filter were considered separately as lumped masses supported by weightless elastic columns fixed at the foundation. Only shear deformation was used in determining the elastic properties of the columns. Figure 8.19A shows a normal cross section of the sand filter: Figs. 8.19B-D illustrate the types of deformity expected in the filter structure, the filter material, and the berm, respectively. The results are summarized in the tabulation in Fig. 8.19E (ibid., Supplement I, Sect. IV, pp. 8, 10, 11, and 13).

The filter materials and the berm show a similar response, whereas the filter structure is somewhat more flexible. A loading on the structure walls results when the filter structure moves, since it is equally restrained by the filter material and the berm. Although the actual shape of the load pattern is unknown, an equivalent uniform-loading pattern assumed for design purposes would result in

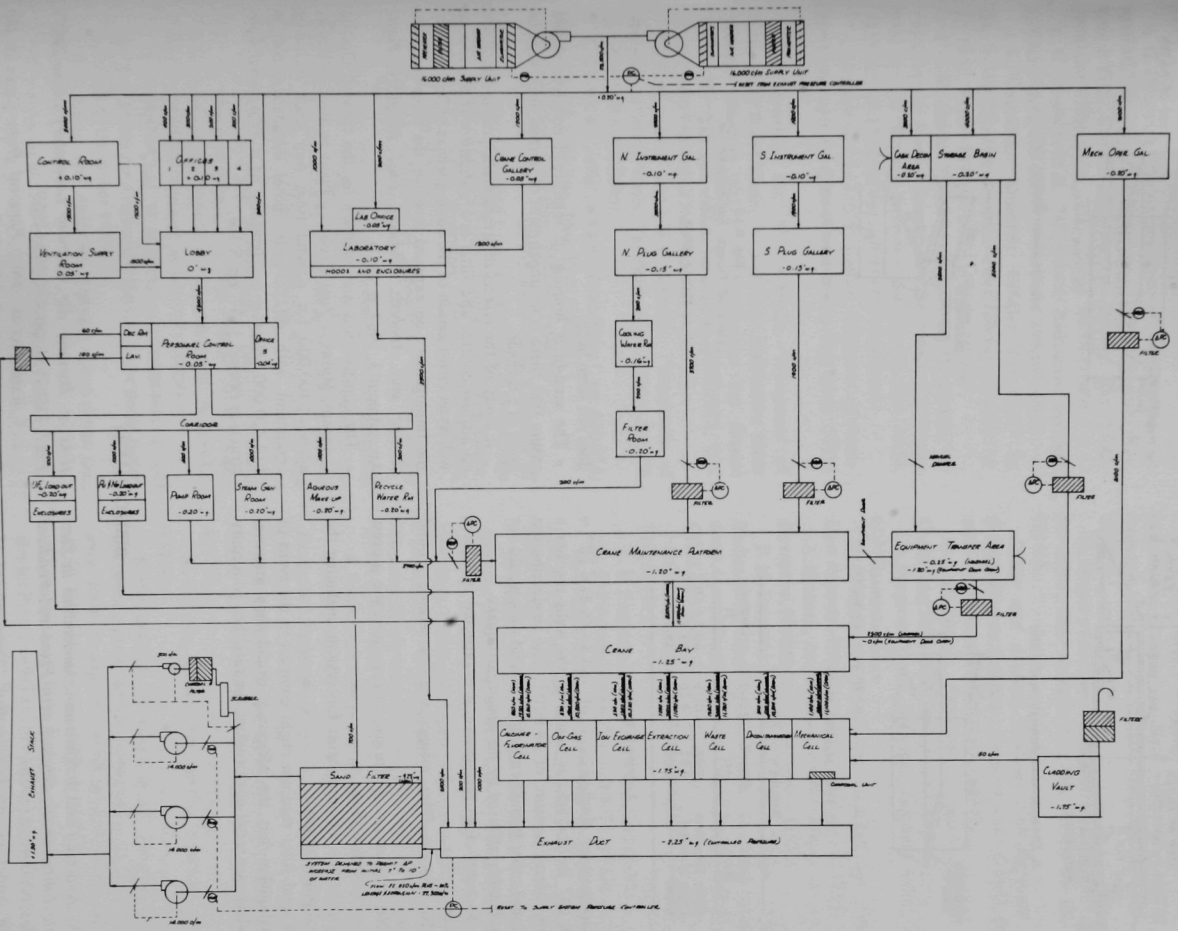
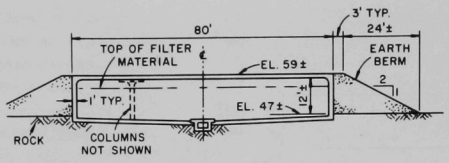
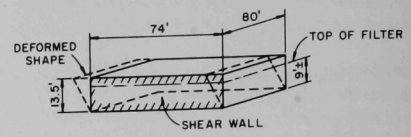


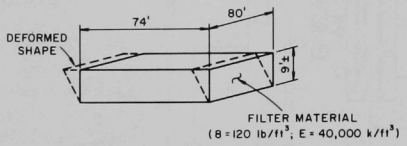
Fig. 8.18. Ventilation System Flow Diagram (Design and Analysis, Midwest Fuel Recovery Plant, 1966).



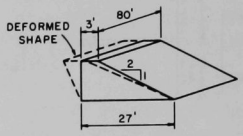
A. Cross Section through Sand Filter



B. Structure Alone



C. Filter Material Alone



D. Berm Alone

Summary of Response

Item	Period, sec	Accel, g's	Displac, ft
Filter Structure	0.03	0.10	63.5×10^{-6}
Filter Material	0.02	0.10	54.5×10^{-6}
Berm	0.02	0.10	48.4×10^{-6}

E. Seismic Review

Fig. 8.19
Effect of Design Earthquake on Sand Filter for Midwest Fuel Recovery Plant (1949).

a filter-structure displacement of $(63.5 - 48.4) \times 10^{-6} = 15.1 \times 10^{-6}$ ft. The seismic design of the walls requires a uniform lateral pressure of 30 lb/ft^2. The air-distribution tunnel and other tunnels embedded in solid rock would not be significantly affected by the design earthquake.

In the event of an earthquake, it is expected that there would be:

1. No loss in filter efficiency from seismic ground motion.

2. No impairment of normal airflow from the process area to the exhaust fans.

3. No failure of an exhaust fan system, including the essential power supply.

The sand filter medium might compact in the event of an earthquake, but the efficiency would then improve; channeling as a result of disrupting the filter-bed continuity does not seem likely.

The sand-filter housing of reinforced concrete should ensure that there is no impairment of normal airflow in the event of a tornado.

A study of the effects of atmospheric-pressure gradients on airflow control and filter-bed stability was planned, as well as an investigation of the consequences of possible missile impingement on exposed areas of the filter structure, (*Design and Analysis, Midwest Fuel Recovery Plant,* Amendment 3, 1967, p. 11-1).

The construction cost estimate for the General Electric Company Midwest Fuel Recovery Plant at Morris, Illinois, allows $400,000 for a sand filter and stack including equipment with 60,000 cu ft. Total installation cost is $14,420,000 (*Hearing on Issuance of a Provisional Construction Permit,* 1967, pp. 8-10).

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